DIVISION OF THE HUMANITIES AND SOCIAL SCIENCES
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91125

COMPARING MODELS OF ELECTRIC UTILITY BEHAVIOR

Geoffrey Rothwell

SOCIAL SCIENCE WORKING PAPER 588

November 1985

ABSTRACT

Several models of electric utility behavior have been suggested and tested. Among them are profit and revenue maximization and cost and revenue minimization. The latter being the stated objective of many public utilities. These four models are compared empirically by examining power plant choice from 1970 to 1977. The net present value (profit) model yields the highest estimated likelihood and its parameters are consistent with _a priori_ theory. Firms were attempting to maximize their return, while minimizing fixed and variable costs. Also, I find no evidence that the difference between the allowed rate of return and the cost of capital influenced technology choice.

COMPARING MODELS OF ELECTRIC UTILITY BEHAVIOR*

Geoffrey Rothwell
California Institute of Technology

Although the electricity generation and distribution industry has been the subject of many investigations, there is surprisingly little consensus regarding the behavioral objectives of electric utilities. The two most popular models in empirical studies are (1) cost minimization subject to a production constraint and (2) profit maximization subject to an allowed rate-of-return constraint. Considering only some of the studies since 1978: static cost minimization was used in Belinfante (1978), McFadden (1978), Stevenson (1980), and Gollop and Roberts (1981). Single-period profit maximization under rate-of-return regulation was the maintained

hypothesis in Cowing (1978), Smithson (1978), Atkinson and Halvorsen (1980), and Cowing (1982). Also, Cowing, Small, and Stevenson (1981), Nelson and Wohar (1983), and Nelson (1984) used cost minimization subject to the allowed rate-of-return constraint. Others have been proposed: <u>ex ante</u> fixed cost minimization with ex variable cost minimization in Fuss (1978) and multi-period profit maximization in Gollop and Karlson (1980). On studies before 1978, see Cowing and Smith (1978) and Rothwell (1985), Chapter 2.

Unfortunately, most authors usually compare two non-nested models when making conclusions about firm behavior. If profit maximization is rejected, the writer generally concludes that firms must have been minimizing cost, without considering that they could have been operating under another behavioral objective, such as revenue maximization. This paper contrasts four models of behavior in a nested framework: profit maximization, revenue maximization, cost minimization, and revenue minimization.

Each model can be associated with one or more actors: owners, managers, regulators, or customers. Owners would prefer the firm to behave such that profit, or net present value, is maximized. Managers, as owners' agents, should maximize profit. But given incentive structures, e.g., inter-firm promotion tied to firm sales, managers may act to maximize revenues. The ideal regulator can be modeled as promoting cost-minimization (although this is open to debate). Lastly, customers would prefer revenue minimization, i.e., the lowest cost to the consumer.

---

* I would like to thank the following people for their valuable comments and support: R. Gilbert, J. Henly, P. Joskow, T. Keeler, P. Messinger, R. Noll, J. Quigley, N. Polin, and P. Ruud. This research was supported by a grant from the University-wide Energy Research Group, University of California, and by the California Institute of Technology. Previous versions were presented at the Western Economics Association's 1985 conference and to the Technology Innovation Project seminar at Stanford University. This paper reflects my own views and errors, and not those of these individuals or institutions.

Although there may be differences in short and long-run behavior, I assume that all are acting in their long-run interest. For example, customers would support allowed rates of return that assure the firms' the long-run viability. Also, considering regulatory institutions, I assume that regulators influence technology choice only through the allowed rates of return on construction expenditures and the rate base. However, they are also involved in plant selection through "Public Convenience and Necessity" hearings. Even through these proceedings are not explicitly modeled here, I assume that in the hearings regulators would act in a manner consistent with their decisions regarding rates of return.

This paper attempts to determine the model that bests describes power plant technology selection. In the first two sections, I examine the choice of a generating technology under each model given a predetermined level of capacity expansion and a constant elasticity of demand. Section 3 discusses how the models are nested and how they can be compared. The fourth section identifies a maximum likelihood estimator to empirically distinguish between objective functions by examining nuclear and coal unit choice from 1970 to 1977. Section 5 presents my estimation results: the net present value maximization model yields the highest likelihood and its estimated parameters are consistent with a prior theory. In the last section, I investigate the influence of rate-of-return regulation. I find that the difference between the allowed rate of return and the cost of capital had no effect on power plant choice.

1. MAXIMIZATION MODELS

Although many economists assume that electric utilities have a continuous production possibilities frontier, this is an inappropriate representation of technology choice facing firms in this industry. More realistic is the assumption that firms are constrained to choose among a discrete number of technologies in providing a given level of capacity. This approach has been used by Joskow and Mishkin (1977) and Ellis and Zimmerman (1983).[1] The method assumes that *ex ante* choices are made among technologies with fixed *ex post* input ratios. The problem for the researcher becomes one of modeling the *ex ante* decision-making process. In this and the next section, I consider four behavioral models. Throughout this discussion I assume that the amount of capacity is determined exogenously to the technology choice decision and that firms face a constant elasticity of demand across technologies.

The Net Present Value of a Power Plant

The profit maximization model holds that a privately owned electric utility maximizes the firm's value to its owners by choosing the generating technology that yields the highest net present value subject to an allowed rate of return. I assume that the firm considers each turbine-generator unit as an independent project. Although a plant is composed of one or more units, I will use the terms "plant" and "unit" interchangeably. Also, I do not consider taxes or decommissioning costs.[2] With these caveats, I show that the net present value of a power plant can be represented as a function of the allowed rate of return (s), the discount rate (r), the depreciation rate (d), the distribution of construction expenditures over time (n_t), the lead time of construction (L), the plant's lifetime (T), and the total cost of plant structures and equipment (CT).

The net present value, NPV_0, is the sum of cash flows to the firm over the plant's life discounted to year 0, the year in which the firm decides to construct the generating unit. To compare technology adoption decisions across firms, NPV_0 is expressed in dollars per kilowatt-hour.[3] Let construction start at t = 1 and continue to L, when the plant enters the rate base. Further, let T be the date of retirement. So, cash flows can be broken into two periods: construction from 1 to L and operation from (L + 1) to (L + 1 + T). Let L+ = L + 1 and T+ = L + 1 + T. If there is only one addition to the rate base at L+ :

$$NPV_0 = \sum_{t=L+}^{T+} \frac{CF_t}{(1 + r)^t} - \sum_{t=1}^{L} \frac{CX_t}{(1 + r)^t} , \tag{1}$$

where CF_t are the cash flows to the firm from t = L+ to T+, CX_t are construction expenditures on the power plant from t = 1 to L, and r is the discount rate at time 0.

The cash flows are equal to total revenues, RV_t, minus expenses, EX_t, i.e., $CF_t = RV_t - EX_t$. Under regulation, total revenues equal the allowed rate of return, s, on the rate base, RB_t, plus depreciation, DB_t, plus EX_t: $RV_t = s \cdot RB_t + DB_t + EX_t$, where I assume that firms use a single value for s over the plant's life. The cash flow from L+ to T+ is equal to the return on the rate base plus depreciation, i.e., $CF_t = s \cdot RB_t + DB_t$. Notice this formulation assumes that rates are automatically adjusted for changes in EX_t. I drop this assumption at the end of this section.

In the first year of operation, RB_L is equal to the plant's cost, PT.[4] In each year, the rate base decreases with depreciation. I model depreciation with the straight-line method at a depreciation rate of d. So, the amount of depreciation is uniform over the plant's life. The annual depreciation is equal to the product of d and PT. Under these conditions, $RB_t = [1 - d \cdot (t - L - 1)] \cdot PT$.[5] The cash flow during each year is a function of s, d, L, and PT:

$$CF_t = PT \cdot (s \cdot [1 - d \cdot (t - L - 1)] + d) . \tag{2}$$

Next, I introduce the convention of representing yearly expenditures as a fraction of total expenditures, i.e., $CX_t = m_t \cdot PT$, where the m_t are percentage expenditure weights related to PT. With this simplification, NPV_0 can be represented as

$$\begin{aligned} NPV_0 &= PT \cdot \sum_{t=L+}^{T+} \frac{[s + d - s \cdot d \cdot (t - L - 1)]}{(1 + r)^t} \\ &\quad - PT \cdot \sum_{t=1}^{L} \frac{m_t}{(1 + r)^t} \\ &= PT \cdot SD - PT \cdot MD \end{aligned} \tag{3}$$

where

$$SD = \sum_{t=L+}^{T+} \frac{[\, s + d - s \cdot d \cdot (t - L - 1)\,]}{(1 + r)^t} ,$$

$$MD = \sum_{t=1}^{L} \frac{m_t}{(1 + r)^t} ,$$

Equation (3) must be adjusted for the regulation of firm investment. There are two regulatory methods to compensate the utility for the cost of capital during construction. They are Allowance for Funds Used During Construction (AFUDC) and Construction Work In Progress (CWIP, pronounced "quip"). Under AFUDC, the firm accumulates financing costs in the AFUDC account at a rate of return equal to a weighted cost of debt and equity. This is the AFUDC rate, a. The account is added to the rate base when the plant is completed. Under CWIP, construction expenditures are added to the rate base at the next rate hearing. In the following two sub-sections, I adjust the net present value calculation for AFUDC and CWIP regulation. For a more complete discussion of AFUDC and CWIP, see Rothwell (1985), Chapter 1.

NPV Under AFUDC Regulation

With AFUDC regulation, total plant cost, PT, is the sum of construction expenditures, CT, plus the AFUDC account at time L. I approximate AFUDC during a particular year by averaging expenditures at the beginning and end of the year, i.e., CX_t / 2, and multiplying by the AFUDC rate.[6] Although AFUDC is granted on previous

expenditures, I assume that there is no compounding of AFUDC from one year to the next.[7] Then,

$$\begin{aligned} PT &= \sum_{t=1}^{L} \left(CX_t + a \cdot \frac{CX_t}{2} + a \cdot \sum_{j=1}^{t-1} CX_j \right) , && (4) \\ &= CT + \left(a \cdot \frac{CT}{2}\right) + \left(a \cdot CT \cdot \sum_{t=1}^{L} \sum_{j=1}^{t-1} n_j \right) = CT \cdot (1 + A) \end{aligned}$$

where

$$A = a \cdot \left(\frac{1}{2} + \sum_{t=1}^{L} \sum_{j=1}^{t-1} n_j\right) \quad \text{and} \quad n_t = \frac{CX_t}{CT} .$$

Adjusting the rate of expenditure, m_t, for AFUDC, let MD = ND · (1 + A). Substituting for PT and MD in equation (3): NPV_a = CT · (1 + A) · SD − CT · ND, where NPV_a is the net present value under AFUDC regulation at time 0.

NPV Under CWIP Regulation [8]

The net present value under CWIP, NPV_c, is CT · (SD − ND) plus the sum of discounted cash flows during construction, CF_c. The revenues in period t, CF_{ct} ($t \leq L$), are a function of the cumulative value of construction expenditures:

$$CF_{ct} = s \cdot \sum_{j=1}^{t-1} CX_j = s \cdot CT \cdot \sum_{j=1}^{t-1} n_j , \qquad (5)$$

where the summation extends to (t − 1), instead of t, because expenditures during one year do not enter the rate base until the next year.[9] Note that CWIP is not depreciated until the plant enters commercial service. The total discounted return to CWIP during construction is

$$CF_c = CT \cdot \sum_{t=1}^{L} \sum_{j=1}^{t-1} \frac{s \cdot n_j}{(1 + r)^t} \qquad (6)$$

$$= CT \cdot SN ,$$

where SN is appropriately defined. Then $NPV_c = CT \cdot [SD + SN - ND]$. To summarize net present value maximization, I introduce a parameter, Δ, which is equal to 1 under AFUDC and equal to zero under CWIP:[10]

$$NPV = CT \cdot SD + \Delta \cdot CT \cdot A \cdot SD \qquad (7)$$

$$+ (1 - \Delta) \cdot CT \cdot SN - CT \cdot ND ,$$

Regulatory Lag

Finally, consider the problem of regulatory lag in compensating the firm for increases in variable costs. During the mid-1970s, firms faced high inflation rates for fuel and labor. Under regulation before automatic fuel adjustment clauses, rates were based on costs experienced in a prior test year. This would mean that firms could not raise rates until after they experienced a rise in costs. While it is difficult to determine expected losts under regulatory lag, a net present value maximizer would prefer technologies with lower variable costs, because the lower the variable cost, the smaller the absolute loss under inflation. To represent this loss, I introduce a parameter, β, on the discounted value of variable expenses. The discount multiplier is the geometric series, present worth factor. For the first year of operation it is equal to

$$\frac{[\,1 - (1 + e)^T \cdot (1 + r)^{-T}\,]}{(r - e)} ,$$

where e is the price escalation rate. If e = r, then T / (1 + r) is used. Further, this is brought to year 0 with $(1 + r)^{-L}$:

$$ED = EX \cdot \frac{[1 - (1 + e)^T \cdot (1 + r)^{-T}\,]}{[(r - e) \cdot (1 + r)^L]} ,$$

where ED are the discounted variable expenses at the time of technology selection. With this addition, equation (7) becomes

$$NPV = CT \cdot SD + \Delta \cdot CT \cdot A \cdot SD \qquad (7')$$

$$+ (1 - \Delta) \cdot CT \cdot SN - CT \cdot ND - \beta \cdot ED .$$

Revenue Maximization

Revenue maximization subject to an allowed rate of return was discussed in Baumol and Klevorick (1970) and Bailey and Malone (1970). Also, Fox (1975) found that between 1960 and 1967, electric utilities behaved like revenue maximizers constrained by their cost of capital.

Revenues are equal to the return on the rate base plus depreciation plus expenses. The discounted total revenues under AFUDC regulation, DTR_a, per kilowatt hour are

$$DTR_a = \sum_{t=L+}^{T+} \frac{(s \cdot RB_t + DB_t + EX_t)}{(1 + r)^t} \qquad (8)$$

$$= CT \cdot (1 + A) \cdot SD + ED$$

Similarly, discounted total revenues under CWIP regulation, DTR_c, equal CT · (SD + SN) + ED. Notice the differences between DTR and NPV: DTR does not include investment expenditures, ND, because they are not directly charged to customers. These expenditures are recovered through the return on the rate base and through depreciation. On the other hand, firms behaving as revenue maximizers prefer greater variable expenses, unlike firms maximizing profit operating under regulatory lag.

2. MINIMIZATION MODELS

Next, consider the cost and revenue minimization models. The cost model has at least three variants: minimization of discounted total costs (DTC), minimization of discounted fixed costs (DFC), and minimization of discounted variable costs (DVC). The first has been used extensively in previous empirical investigations of electric utility technology choice. Fixed-cost, or capital-cost, minimization, (as a reaction to inadequate rates of return) has been proposed by some electric utility executives and is discussed in Chao, Gilbert, and Peck (1984). The minimization of variable cost was suggested by Joskow and Mishkin (1977), p. 733, to explain their statistical results. Further, these models can be interpreted in the Fuss (1978) framework: DFC is the _ex ante_ minimization of fixed costs and DVC is the _ex poste_ minimization of variable costs.

The discounted total cost model can be represented as

$$\begin{aligned} DTC &= \sum_{t=1}^{L} \frac{CX_t}{(1+r)^t} + \sum_{t=L+}^{T+} \frac{EX_t}{(1+r)^t} \qquad (9) \\ &= CT \cdot ND + ED \, , \end{aligned}$$

Note that under DFC the firm minimizes the present value of construction expenditures per kilowatt-hour, CT · ND, and that under DVC the firm minimizes the present value of expenses per kilowatt-hour during the plant's lifetime, ED. Given that DTC = DFC + DVC, the latter two models are nested within the former, allowing easy comparison. Because both AFUDC and CWIP regulation increase cash flows to the firm, but do not increase costs, these models are the same under both forms of regulation.

Required Revenues

Although economists have suggested revenue maximization as one way of describing regulated firm behavior, the electric utility industry has proposed another objective function: minimization of revenue. The technique of required revenue minimization, i.e., the minimization of revenues required for successful operation, was developed in Jeynes (1968) and EPRI (1978), where successful operation was defined in _U.S. FPC v. Hope Natural Gas_, 320 U.S. 591 (1944). In _Hope_ the court held that rates should enable the company to maintain its financial integrity, to attract capital, and to compensate its investors for risk. The model is used so extensively by electric utilities that many firms have a revenue requirements department, for example, at Pacific Gas and Electric in California. I label the revenue minimization model as Discounted Required Revenue (DRR). When choosing among technologies under DRR, the firm attempts to minimize the variables found in the total revenue maximization model, i.e., under AFUDC: min [CT · (1 + A) · SD + ED] and under CWIP: min [CT · (SD + SN) + ED]. Hence, DRR and DTR must be distinguished by the signs of the estimated parameters. Until they are distinguished, I will refer to both models as DRV, discounted revenues.

3. COMPARING MODELS

The four models can be compared most easily when they are nested. For example, the revenue model is nested within the profit model, and the variable cost model is nested within the revenue model. When two models are nested, their equivalence can be determined by considering the difference in their estimated log likelihoods. Two times this difference is distributed as a χ^2, with degrees of freedom equal to the number of restrictions. I will refer to the value as "Statistic" in Table 3, discussed in Section 5. To estimate the likelihood of each model, I examine the choice between nuclear and coal technologies by the electric utilities from 1970 to 1977. Unlike technology diffusion models where the adoption of a particular technology usually depends on <u>industry</u> characteristics, here, the maximizing (minimizing) <u>firm</u> adopts technology 1, if its value is greater (less) than the other option.

I follow the specification of Ellis and Zimmerman (1983) by allowing parameters to vary across technologies, i.e., firms weigh information on decision variables differently for each technology.[11] Let V_j represent the value of technology j to the firm and let β_{ij} be -1, 0, +1, or -β (the parameter associated with regulatory lag in NPV), according to the model under consideration. For two technologies the firm is interested in the difference between V_1 and V_2 :

$$\begin{aligned} V_1 - V_2 = {} & \beta_{11} \cdot CT_1 \cdot (SD_1 + \Delta \cdot A_1 \cdot SD_1 + (1 - \Delta) \cdot SN_1) \\ & - \beta_{12} \cdot CT_2 \cdot (SD_2 + \Delta \cdot A_2 \cdot SD_2 + (1 - \Delta) \cdot SN_2) \\ & + (\beta_{21} \cdot CT_1 \cdot ND_1 - \beta_{22} \cdot CT_2 \cdot ND_2) \\ & + (\beta_{31} \cdot ED_1 - \beta_{32} \cdot ED_2) . \end{aligned} \tag{10}$$

As presented in this equation, the expected signs are

$$\begin{array}{lcll} \text{NPV:} & [\beta_{1j}, \beta_{2j}, \beta_{3j}] & = & [\ +1, \ -1, \ -\beta\ ] \\ \text{DTR:} & [\beta_{1j}, \beta_{2j}, \beta_{3j}] & = & [\ +1, \ 0, \ +1\ ] \\ \text{DRR:} & [\beta_{1j}, \beta_{2j}, \beta_{3j}] & = & [\ -1, \ 0, \ -1\ ] \\ & & & \\ \text{DTC:} & [\beta_{1j}, \beta_{2j}, \beta_{3j}] & = & [\ 0, \ -1, \ -1\ ] \\ \text{DFC:} & [\beta_{1j}, \beta_{2j}, \beta_{3j}] & = & [\ 0, \ -1, \ 0\ ] \\ \text{DVC:} & [\beta_{1j}, \beta_{2j}, \beta_{3j}] & = & [\ 0, \ 0, \ -1\ ] \end{array}$$

Although Joskow and Mishkin (1977) and Ellis and Zimmerman (1983) introduce two discounted expense (ED) variables, one for fuel costs and the other for operation and maintenance expenses, their models are most similar to total cost minimization, DTC. Joskow and Mishkin examined fossil fuel plants built between 1952 and 1965. They found that as variable expenses for a particular technology increased, the probability of adopting that technology decreased. They did not find the parameter associated with the capital cost variable to be significant. On the other hand, Ellis and Zimmerman, examining coal and nuclear plant orders from 1970 to 1978, found that only the parameters associated with coal operating and maintenance costs and nuclear capital costs to be significant, positive and negative, respectively. Given that the parameter on coal fuel cost was also positive, although with a t-statistic of only 1.14, the parameter on ED_2 should be positive (or negative if ED_2 is subtracted). In section 5, I give my estimation results. The parameters generally conform to these expectations. However, before further discussion, I present the estimator.

4. THE PROBABILITY OF TECHNOLOGY CHOICE

In discussing the estimator, I follow Hausman and Wise (1978) and Daganzo (1979). Let X_{ij} be a vector of characteristics related to technology j as perceived by firm i. Some of these are constant across all firms, e.g., the plant's lifetime, T_j. Others are estimated for each firm. These are the lead time, the AFUDC mark-up, the construction cost, and variable expenses (L_{ij}, A_{ij}, CT_{ij}, and EX_{ij}). Also, there are attributes, α_i, that are firm specific and constant across all technologies. These are the weighted cost of capital for firm i, r_i, the AFUDC rate, a_i, and the allowed rate of return, s_i.[12] (These data are described in the Appendix.) Using this notation, the probability of choosing technology 1, τ_1, is

prob[$V_1(X_{i1}, \alpha_i) > V_2(X_{i2}, \alpha_i)$]. The technology characteristics and firm attributes are transformed into parameters and variables, β_{kj} and Z_{ijk}, where k ranges from 1 to 3. By comparing observed choices with the Z_{ijk}, the parameters are estimated using a maximum likelihood technique. (Note that the β_{kj} are parameters for the average firm.)

Further, there are unobserved characteristics for each technology that may increase or decrease the value of a generating unit. Let the sum of the neglected variables be equal to β_0, a constant component, plus $\tilde{\varepsilon}$, a random term. I assume that the $\tilde{\varepsilon}$ are normally distributed with mean zero and variance σ_ε^2. Then, $\tilde{e}$ is normally distributed with mean β_0 and variance σ_ε^2. So, the probability of adopting τ_1 is

$$\text{prob}[\ \beta_{01} + \sum_k Z_{i1k} \cdot \beta_{k1} + \tilde{\varepsilon}_1 > \beta_{02} + \sum_k Z_{i2k} \cdot \beta_{k2} + \tilde{\varepsilon}_2\ ] \quad (11)$$

This expression can be rearranged by moving the non-stochastic terms to one side and the random terms to the other:

$$\text{prob}[\ \beta_0 + \sum_k Z_{i1k} \cdot \beta_{k1} - \sum_k Z_{i2k} \cdot \beta_{k2} > \tilde{\eta}\ ] . \quad (12)$$

where $\beta_0 = \beta_{01} - \beta_{02}$ and $\tilde{\eta} = (\tilde{\varepsilon}_2 - \tilde{\varepsilon}_1)$. If the $\tilde{\varepsilon}_j$ are normal, then $\tilde{\eta}$ is the sum of normal variates, and is thus normal itself. If I assume that the normal variates have zero means, then $\tilde{\eta}$ has a mean of zero and a variance of σ_η^2. Dividing both sides of the inequality in equation (12) by σ_η, yields a N(0, 1) variate on the left hand side. Let

$$D_{i1} = \frac{[\ \beta_0 + \sum_k Z_{i1k} \cdot \beta_{k1} - \sum_k Z_{i2k} \cdot \beta_{k2}]}{\sigma_\eta} .$$

Then the probability, P_{i1}, of observing τ_1 is equal to the cumulative probability of observing D_{i1} :[13]

$$P_1 = \int_{-\infty}^{D_1} \phi(\tilde{\eta})\, d\tilde{\eta} = \Phi(D_1) , \tag{13}$$

where $\phi(\tilde{\eta})$ is a standard normal density function and $\Phi(D_1)$ is a standard normal cumulative distribution function.

Estimation is done with binary probit.[14] If the observations can be appropriately modeled as a sample of independent drawings, the log of the likelihood function is equal to

$$\log L = \sum_{i=1}^{N} \sum_{j=1}^{2} \tau_{ij} \cdot \log P_{ij} ,$$

where N is the sample size and $\tau_{ij} = 1$ if firm i chooses technology j and equal to zero otherwise. Across a sample of technology choices, the probit estimator selects values for $(\beta_{kj} / \sigma_\eta)$ that maximize the likelihood of observing the realized outcomes. Note that with probit the β_{kj} are not identifiable without some a priori specification of the elements of σ_η. Given that I have no such a priori information, I normalize (σ_η) to one. Although the scale of an estimated parameter is unidentified, the sign of the estimate can be identified. Further, the ratio of two coefficients is also identifiable. This precludes drawing certain conclusions, but my primary objective is to evaluate the explanatory power of each model. I do this by comparing the estimated values of the likelihood functions.

5. RESULTS

I am interested in determining the model that best describes the technology adoption behavior of electric utilities during the 1970s. This can be done in two ways. In some situations the models are nested. This allows testing by constraining certain parameters to zero. In other cases, models can be distinguished only by the signs of the estimated coefficients. For these, I rely on asymptotic t-statistics. To aid this discussion, correlation coefficients are presented in Table 1. Also, Table 2 shows the estimated parameters; and Table 3 compares the estimated models. In the latter, a contrast is made between the log of the likelihood values at convergence for the unrestricted and the restricted models. The acceptance or rejection of the null hypothesis is shown in the last column. To allow visual comparison among the models, there are diagrams accompanying each table. Where the null hypothesis is rejected, arrows point in the direction of the dominant model, i.e., the model with the higher log likelihood.

Estimated Likelihoods

Considering the cost minimization models, the total cost and fix cost models appear to be equivalent, while DTC dominates the variable cost model. See the first row of Table 3. Also, notice the low correlation between the dependent variable, CHOICE, and the discounted variable expenses (ED_1 and ED_2) in Table 1. There are at least two reasons for this: (1) During the 1970s, firms may have been more interested in capital costs than in variable costs. A reasonable conclusion given the financial condition of many utilities during that period. But this seems to contradict the findings of Joskow and Mishkin (1977), i.e, during the 1950s and 1960s, capital costs did not appear to play a significant role in power plant technology selection. Hence, there may have been a change in electric utility behavior between 1965 and 1970. Or, (2) expected variable costs may not be well modeled because of the uncertainty in the rates of increase in fuel prices that persisted throughout the 1970s. I have calculated fuel prices in 1980 dollars using realized inflation rates. These rates could differ widely from expected rates at the time of technology selection.

The cost models are also compared with the profit and revenue models in Table 3. Given the results regarding the insignificance of the variable cost parameters, it is not surprising to find that the revenue model, DRV, dominates DVC. Although equivalence of DFC and DTC with the profit model, NPV, is rejected at the 95% level, equivalence would not be rejected at the 97.5% level. (But, as I show

in the next section, reestimation with a slightly different specification yields rejection at the 99% level.) The closeness of DTC and DFC to NPV is a result of the correlation between the SD_j and ND_j, i.e., the likelihood changes little with the addition of SD_j to models with ND_j.

This closeness is also found in the comparison of DRV and NPV. Although one can reject their equivalence at the 97.5% level with this specification, equivalence cannot be rejected at the 95% level under a slightly different specification. Also, notice that while DTC and DFC cannot be compared directly with DRV, the log likelihoods of all three models are similar. In sum, while the profit model appears to be the best description of electric utility behavior, it is difficult to rank the other models based on their estimated likelihoods. Thus, I turn to the parameters' signs.

Estimated Parameters

In Section 3, I presented the expected signs of the parameters for each model. Here, I discuss the β_{kj}, beginning with the parameters associated with the discounted variable costs. Although I found that the ED_j did not play a significant role in technology choice, the signs of β_{31} and β_{32} are not always insignificant. When significant, they are negative. This supports the findings of Joskow and Mishkin (1977) and of Ellis and Zimmerman (1983).[15] It implies minimization of variable costs, lending support to the cost and revenue minimization models. But notice that the β_{3j} are both positive, although insignificant, in DVC. So, DVC should be rejected because its parameters do not conform to a priori expectations.

Next, consider the capital cost (ND_j) and rate base (SD_j) variables. In the total and fixed cost models, the β_{2j} are positive. In the profit and revenue models, the β_{1j} are positive and significant, while the β_{2j} are negative in NPV.[16] The β_{2j} could be positive in the cost models because the ND_j are proxies in the cost models for the return on the rate base, SD_j. Thus DTC and DFC are rejected because they too do not support a priori theory. Further, neither revenue maximization or minimization can be accepted. Revenue maximization is rejected because firms were minimizing variable costs. Revenue minimization is rejected because firms were maximizing the return on the rate base. Apparently, firms were attempting to maximize the return on the rate base while minimizing fixed and variable costs. Thus, the only model that satisfies a priori expectations is the profit (net present value) model. This is similar to the conclusion reached above, i.e., while it is difficult to choose among the cost and revenue models, the profit model most accurately describes firm behavior. But if firms were maximizing profit, was there a tendency toward overcapitalization? I discuss this question in the next section.

6. THE ALLOWED RATE OF RETURN

Given the dominance of the profit maximization model: did the allowed rate of return significantly influence technology choice? Or, does a large difference between the allowed rate of return (s) and the cost of capital (r) influence firm behavior? According to the model proposed in Averch and Johnson (1962), the difference should affect the choice of factor inputs. As Baumol and Klevorick (1970) show, smaller differences should lead to overcapitalization.

To distinguish between the allowed rate of return and the cost of capital, let v = s − r. I substitute for s = r + v in SD and SN in equations (3) and (6).

$$\begin{aligned} SD &= \sum_{t=L}^{T} \frac{[\, r + d - [r \cdot d \cdot (t - L) \,]}{(1 + r)^t} \\ &+ \sum_{t=L}^{T} \frac{[\, v - v \cdot d \cdot (t - L) \,]}{(1 + r)^t} \\ &= RD + VD \; ; \quad \text{and} \end{aligned} \tag{14}$$

$$\begin{aligned} SN &= r \cdot \sum_{t=1}^{L} \sum_{j=1}^{t-1} \frac{n_j}{(1 + r)^t} + v \cdot \sum_{t=1}^{L} \sum_{j=1}^{t-1} \frac{n_j}{(1 + r)^t} \\ &= RN + VN \, . \end{aligned} \tag{15}$$

I introduce a parameter, ρ, to examine reaction to the difference between the allowed rate of return and the cost of capital: $SD = RD + \rho \cdot VD$ and $SN = RN + \rho \cdot VN$. Previously, I have assumed that $\rho = 1$. To test the significance of the rate of return premium (v) I estimate ρ using a non-linear specification and compare the log likelihood to models where $\rho = 1$ and $\rho = 0$.[17] Parameters and likelihoods are presented in Table 4.

The log likelihoods are compared in Table 5. All models where ρ is constrained to zero are equivalent to models where ρ is unconstrained. Where $\rho = 1$, equivalence between the constrained and unconstrained models would be rejected at the 90% level. This means that the specification of an unconstrained ρ and ρ constrained to zero are superior to the previous implied specification of $\rho = 1$. Under these new specifications, NPV and DRV appear to be equivalent (although this would be rejected at the 90% level) and their log likelihoods are significantly higher than those of the cost models. For example, the equivalence of the profit and total cost models is rejected at the 99% level. Therefore, ρ, the preference weight on the allowed rate of return premium, does not appear to be significantly different from zero. In choosing between nuclear and coal technologies, firms were not influenced by the allowed rate of return premium.

CONCLUSIONS

In summary, I find evidence to conclude that net present value (profit) maximization best explains electric utility technology choice during the 1970s. This was shown by comparing the log likelihoods of the profit, revenue, and cost models and by examining the signs of the estimated parameters. Firms appear to have been choosing technologies to maximize their return on the rate base, while minimizing fixed and variable costs.

These results are consistent with almost all the empirical studies in this area. Cost minimization was rejected in Spann (1974), Courville (1974), Petersen (1975), Cowing (1978), Atkinson and Halvorsen (1980), and Cowing (1982). I have also rejected cost minimization. Further, the parameter attached to the allowed rate of return premium was insignificant in Boyes (1976), Smithson (1978), Gallop and Karlson (1980), Nelson and Wohar (1983), and Nelson (1984). I have also found the allowed rate of return parameter to be insignificant. While accepting profit maximization, I reject the influence of the difference between the allowed rate of return and the cost of capital. Although cost and revenue minimization are rejected, this does not mean that regulation was necessarily ineffective. Regulation may have reduced profit maximizing behavior by electric utilities from what it might have been otherwise. However, it is not surprising to find in an economic system based on profit incentives that regulated firms would be maximizing net present value.

DATA APPENDIX

Between 1970 and 1977 almost all new power plants larger than 100 megawatts employed either nuclear or coal technology. To insure comparability between the two technologies, I only considered generating units greater than 500 megawatts. Further, I was limited to observations with information on the turbine-generator order date. I began with the "Generating Unit Reference File," US DOE tape number PB82-150442, and eliminated units not adhering to these criteria. Also, I deleted multiple units ordered in the same year for the same plant site. This resulted in a sample of 87 observations.

Capital Costs

Given this sample, I collected data on the technologies' characteristics (X_{ij}) and the firms' attributes (α_i). Some of these characteristics were assumed to be constant across firms. These include the distribution of construction expenditures over time, n_{tj}, and the plant's lifetime, T. The n_{tj} for each technology were taken from Komanoff (1980) based on Mooz (1978). The lifetime of a unit is 30 years for each technology, following EPRI (1978), pp. XII-16,17. With straight-line depreciation, the depreciation rate, d, is approximately 0.033.

Three technology characteristics were forecast: the lead time, the AFUDC mark-up, and the construction cost. On-line dates conditional on order dates were predicted from cross-section estimates of lead times (see Rothwell (1985), Chapter 4, Tables 4.6.1 and 4.6.2) using the following form: (log of lead time) = $\beta_0 + \beta_1 \cdot$ (start date) + $\beta_2 \cdot$ (log of size) + $\beta_3 \cdot$ (log of wage rate) + $\beta_4 \cdot$ (log of materials price). The lead time, L_{ij}, is the difference between the order date and the predicted on-line date. The AFUDC mark-up, A_{ij}, was calculated using equation (4). (See the section "NPV Under AFUDC Regulation.") The AFUDC rate is

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

where EC_i is the equity to total capitalization ratio and z_{it} is the realized rate on common equity in period t. The interest rate on debt, i, is from *Moody's* sources. The rate of return on common equity, z, and the capitalization ratio, EC, were from *Statistics of Privately Owned Electric Utilities.* I assumed that r_i and a_i are equal, as suggested by EPRI (1978), p. V-3. Allowed rates of return, s_i, are available in the National Association of Regulatory Utility Commissioners' (NARUC's) annual report on utility regulation, section F: "Basis of Rate of Return."

Plant costs in 1980 dollars, CT_{ij}, for both the nuclear and coal alternatives were predicted from cross-section estimations of Cobb-Douglas cost functions, using parameters from Tables 4.13.1 and 4.13.2 in Rothwell (1985), Chapter 4. The data are similar to those in Zimmerman (1982) and Joskow and Rose (1985). I assumed that the expected capacity factor, CF_{ij}, decreases at a uniform rate from 80 percent in 1970 for both technologies to the values listed for 1980 in US DOE/NBB (1982), p. 16.

Variable Costs

Variable expenses include the cost of fuel and the cost of operation and maintenance. The fuel expense is the product of the total fuel consumed (TF) and the price per unit of fuel (p_f) divided by the annual net generation (Tkwh), i.e., $TF \cdot p_f \,/\, Tkwh$. This can be manipulated to introduce the heat rate (HTR) equal to the energy content of a unit of fuel measured in British Thermal Units (BTU) divided by the annual net generation, i.e., $HTR = (TF \cdot BTU \,/\, Tkwh)$:

$$\frac{TF \cdot p_f}{Tkwh} \cdot \frac{BTU}{BTU} = \frac{TF \cdot BTU}{Tkwh} \cdot \frac{p_f}{BTU} = HTR \cdot F ,$$

where F is the fuel price per BTU. The heat rate for new fossil-fuel plants changed little from 1960 (10,356) to 1980 (10,467), according to the "Steam Station Cost Survey," Electrical World, October 1967 and November 1981. (The average heat rate improved slightly before 1970, then fell back to its 1960 level by 1980.) I assumed that the heat rate for coal units was reasonably approximated by the Electrical World data. For nuclear plants, I used EPRI's assumption of 10,400 as an average annual heat rate. See EPRI (1978), p. XII-17.

The price per BTU of coal for each state was taken from US DOE/NBB (1982), pp. 262-63. These prices were inflated to 1980 dollars using the Bureau of Labor Statistics' Producer Price Index for coal. Given that the price of nuclear fuel changed little from region to region, EPRI's estimate of 0.54 dollars/million BTU was applied to all nuclear plants. This 1977 figure was inflated 1980 dollars with the BLS Producer Price Index for "Fuels, Related Products, and Power." Operation and maintenance expenses are less well defined. They include supervisory, engineering, and maintenance labor, as well as the materials used to maintain plant structures and equipment. Rather than calculating these expenses directly, I increased the estimates of fuel costs by the ratio of total production costs to fuel expenses for nuclear and coal plants for each of seven regions from US DOE/EIS (1982), p. 16. Let total variable costs, EX_{ij}, equal $HTR_{ij} \cdot F_{ij} \cdot TFR_{ij}$, where TFR_{ij} is the ratio of total cost to fuel cost. To calculate the present value of a stream of payments over the plant's lifetime, I assume that coal and nuclear plant variable expenses escalate at the rates of 6.5 and 8.0 percent, respectively. (These are the e in Section 1.) This follows EPRI (1978), pp. XI-3-5.

TABLE 1: CORRELATION COEFFICIENTS

	CHOICE	SD1	SD2	ND1	ND2	ED1	ED2
CHOICE	1.000						
SD1	-0.341	1.000					
SD2	-0.438	0.792	1.000				
ND1	-0.409	0.934	0.753	1.000			
ND2	-0.472	0.705	0.937	0.786	1.000		
ED1	0.185	0.164	-0.045	-0.078	-0.279	1.000	
ED2	0.086	0.146	0.243	-0.056	0.069	0.444	1.000

CHOICE = 1 if nuclear, = 0 if coal

TABLE 2: PARAMETER ESTIMATION RESULTS

	NPV	DRV	DTC	DFC	DVC	
	Profit	Revenue	Total Cost	Fixed Cost	Variable Cost	
B0	5.79**	3.21**	5.47**	4.45**	-1.24**	B0
	(1.77)	(1.15)	(1.61)	(1.05)	(0.57)	
SD1	0.21**	0.03*	xxxx	xxxx	xxxx	B11
	(0.10)	(0.02)				
SD2	0.22**	-0.11**	xxxx	xxxx	xxxx	B12
	(0.09)	(0.04)				
ND1	-0.19*	xxxx	0.03	0.01	xxxx	B21
	(0.10)		(0.02)	(0.02)		
ND2	-0.09	xxxx	0.12**	0.09**	xxxx	B22
	(0.10)		(0.03)	(0.03)		
ED1	-1.29	0.12	-1.59	xxxx	1.23	B31
	(1.39)	(1.04)	(1.22)		(0.81)	
ED2	-2.55	-4.23**	-3.23*	xxxx	0.05	B32
	(2.07)	(1.87)	(1.81)		(1.25)	
LL	-35.67	-39.78	-38.98	-40.65	-56.24	

Log Likelihood (LL) at Zero: -60.30
(Asymptotic Standard Errors)

*: Significant at 90% level
**: Significant at 95% level

TABLE 3: COMPARISON OF LOG LIKELIHOODS

```
   DFC        [1]          DTC        [2]         DVC
 -40.65      -----        -38.98     <-----     -56.24
    |                       |                      |
[3] |                   [4] |                  [5] |
    |                       v                      v
    |                      NPV        [6]         DRV
    +------------>        -35.67     <-----     -39.78
```

	Unrestricted	Restricted	Statistic	df	Critical	Null?
[1]	DTC	DFC	3.34	2	5.99	Accept
[2]	DTC	DVC	34.52	2	5.99	Reject
[3]	NPV	DFC	9.96	4	9.49	Reject
[4]	NPV	DTC	6.62	2	5.99	Reject
[5]	DRV	DVC	32.92	2	5.99	Reject
[6]	NPV	DRV	8.22	2	5.99	Reject

TABLE 4: ESTIMATION RESULTS, RHO CONSTRAINED AND UNCONSTRAINED

	NPV	DRV	NPV	DRV	
	RHO = 0		RHO Unconstrained		
B0	6.04**	6.07**	6.15**	6.19**	B0
	(1.82)	(1.70)	(1.98)	(1.74)	
SD1	0.26*	0.04**	0.26*	0.04*	B11
	(0.14)	(0.02)	(0.16)	(0.02)	
SD2	0.37**	0.15**	0.38**	0.15**	B12
	(0.13)	(0.04)	(0.14)	(0.04)	
ND1	-0.21*	xxxx	-0.21	xxxx	B21
	(0.13)		(0.16)		
ND2	-0.22*	xxxx	-0.22	xxxx	B22
	(0.13)		(0.14)		
ED1	-1.90	-1.96	-2.06	-2.11	B31
	(1.31)	(1.25)	(1.55)	(1.55)	
ED2	-3.03	-4.01**	-2.89	-3.89*	B32
	(2.02)	(1.89)	(2.64)	(2.32)	
RHO	0.00	0.00	-0.08	-0.07	RHO
			(0.37)	(0.42)	
LL	-33.85	-36.37	-33.82	-36.35	

Log Likelihood (LL) at Zero: -60.30
(Asymptotic Standard Errors)

*: Significant at 90% level
**: Significant at 95% level

TABLE 5: COMPARISON OF CONSTRAINED AND UNCONSTRAINED RHO

$$\begin{tikzcd}
 & \text{RHO = 1} & \text{Unconstrained} & \text{RHO = 0} \\
\text{DTC} & & -38.98 \arrow[d, "{[1]}"'] & \\
\text{NPV} & -35.67 \arrow[r, dash, "{[2]}"] & -33.82 \arrow[r, dash, "{[3]}"] \arrow[d, dash, "{[5]}"'] & -33.85 \arrow[d, dash, "{[6]}"'] \\
\text{DRV} & -39.78 \arrow[u, "{[4]}"] \arrow[r, "{[7]}"] & -36.35 \arrow[r, dash, "{[8]}"] & -36.37
\end{tikzcd}$$

	Unrestricted	Restricted	Statistic	df	Critical	Null?
[1]	NPV	DTC	10.32	2	5.99	Reject
[2]	NPV	NPV	3.70	1	3.84	Accept
[3]	NPV	NPV	0.06	1	3.84	Accept
[4]	NPV	DRV	8.22	2	5.99	Reject
[5]	NPV	DRV	5.06	2	5.99	Accept
[6]	NPV	DRV	5.04	2	5.99	Accept
[7]	DRV	DRV	6.86	1	3.84	Reject
[8]	DRV	DRV	0.04	1	3.84	Accept

FOOTNOTES

1. The models developed by these authors are similar to the discounted total cost model (DTC) presented in the Section 2.

2. On taxation, normalized accounting methods, and accelerated depreciation, see Rothwell (1983).

3. This implies that fixed costs are divided by (plant size) x (the hours per year) x (the capacity factor). The capacity factor is the ratio of realized generation to potential generation. It is discussed in the Appendix.

4. Also, there is an allowance for working capital in the rate base. Working capital, as defined by FERC equals (materials and supplies) + (prepayments) + (research and development expenditures) + 0.125 · (operation and maintenance expenses − purchased power) − 0.06 · (federal income taxes). See US DOE, *Statistics of Privately Owned Electric Utilities in the United States*, any year, "Selected Financial Ratios." While prepayments, research and development, and taxes are negligible, materials and supplies and purchased power are not. But these two items should be the same across technologies. However, operation and maintenance expenses will differ. But given that the return to

variable costs are equal to 12.5% of the allowed rate of return, i.e., between 1 and 2% of expenses, the influence on technology adoption should be minimal.

5. This assumes that all plant costs are allowed into the rate base. Although the assumption may be unfounded in the 1980s, it was probably a universally held expectation before 1977, the last year of this study.

6. I assume a uniform expenditure rate during a given year. For empirical work, I calculate AFUDC on a monthly basis.

7. Compounding AFUDC, i.e., granting AFUDC on previous AFUDC, became standard regulatory practice only in the late 1970s. See Pomerantz and Suelflow (1975), p. 174.

8. To simplify modeling, I ignore the offsetting of AFUDC. Under an AFUDC offset, construction expenditures are capitalized, as in AFUDC regulation, and the rate of return on CWIP is set equal to the difference between the allowed rate of return and the AFUDC rate. For a model with AFUDC offset, see Rothwell (1985), Chapter 3.

9. This occurs unless some provision is made for either (1) a future test year or (2) automatic increases subject to refund after the rate hearing. The first still requires returning continually to the regulatory commission. The second has been adopted in some jurisdictions in the 1980s.

10. As an approximation to partial CWIP, let $\Delta = 0.5$ in those states that allow some CWIP in the rate base. A list of these states can be found in Rothwell (1985), pp. 31-33.

11. Preliminary tests showed that this specification was superior to one where parameters were restricted to the same values for both technologies. This implies that firms did not give equal weight to cost information on coal and nuclear plants. It also suggests that there are aspects of the selection process that have not be adequately modeled.

12. I assume that the capital market charges the same risk premium for all technologies. If the level of risk is technology specific, some adjustment for uncertainty must be made. Two approaches have been considered in Rothwell (1984) and Rothwell (1985), Chapter 3.

13. The probability is also a function of observing plant attributes, i.e., the probability density function of the technology attributes. Generally, the density function does not depend on the parameters and can be deleted in the maximum likelihood estimation.

14. I estimated these models with Statistical Software Tools written by Jeffrey Dubin and R. Douglas Rivers of the California Institute of Technology.

15. I have incorporated the negative sign of the coal variables into the estimation, easing the comparison of signs across technologies. For a direct comparison with Ellis and Zimmerman (1983), one must reverse signs on the β_{k2}.

16. The signs and significance of β_{21} and β_{22} in NPV conform to the findings of Ellis and Zimmerman (1983). The coal capital cost parameter is insignificant in both Ellis and Zimmerman and in NPV. Also, the value of their nuclear capital cost parameter is -0.3144 with a standard error of 0.1408. This is close to my estimate of -0.1855 with a standard error of 0.1010.

17. The algorithm was written by Paul Ruud of the University of California, Berkeley, based on Berndt, Hall, Hall, and Hausman (1974).

REFERENCES

Atkinson, Scott E. and Robert Halvorsen, "A Test of Relative and Absolute Price Efficiency in Regulated Utilities," The Review of Economics and Statistics 62, 1 (February 1980) pp. 81-88.

Averch, Harvey and Leland Johnson, "Behavior of the Firm under Regulatory Constraint," American Economic Review 52 (December 1962) pp. 1052-69.

Bailey, Elizabeth E. and John C. Malone, "Resource Allocation and the Regulated Firm," The Bell Journal of Economics 1, 1 (1970) pp. 129-42.

Baumol, William and Alvin Klevorick, "Input Choices and Rate-of-Return Regulation: A Overview of the Discussion," The Bell Journal of Economics and Management Science 1 (Fall 1970) pp. 162-90.

Belinfante, Alexander, "The Identification of Technical Change in the Electricity Generating Industry," in Fuss and McFadden, editors, Production Economics: A Dual Approach to Theory and Applications (Amsterdam: North-Holland Publishing Company, 1978) pp. 146-86.

Berndt, E.K., B.H. Hall, R.E. Hall, and J.A. Hausman, "Estimation and Inference in Nonlinear Structural Models," Annuals of Economic and Social Measurement 3,4 (1974) pp. 653-665.

Boyes, William J., "An Empirical Examination of the Averch-Johnson Effect," Economic Inquiry 16 (March 1976) pp. 25-35.

Chao, H.P., R.J. Gilbert, and S.C. Peck, "Conflicts and Common Grounds: Customer v. Investor Valuation of New Technologies," Public Utilities Fortnightly, (April 26, 1984).

Courville, Leon, "Regulation and Efficiency in the Electric Utility Industry," The Bell Journal of Economics 5, 1 (Spring 1974) pp. 53-74.

Cowing, Thomas, "The Effectiveness of Rate-of-Return Regulation: An Empirical Test Using Profit Functions," in Fuss and McFadden, editors, Production Economics: A Dual Approach to Theory and Applications (Amsterdam: North-Holland Publishing Company, 1978) pp. 215-46.

__________ , "Duality and the Estimation of a Restricted Technology," in Smith, editor, Advances in Applied Micro-Economics (JAI Press: 1982) pp. 191-211.

__________ and V. Kerry Smith, "The Estimation of a Production Technology: A Survey of Econometric Analysis of Steam-Electric Generation," Land Economics 54, 2 (May 1978) pp. 156-86.

__________ , Jeffrey Small, and Rodney E. Stevenson, "Comparative Measures of Total Factor Productivity in the Regulated Sector: The Electric Utility Industry," in Cowing and Stevenson, editors, Productivity Measurement in Regulated Industries (New York: Academic Press, 1981) pp. 162-77.

Daganzo, Carlos, Multinomial Probit (New York: Academic Press, 1979).

Dubin, Jeffrey and R. Douglas Rivers, Statistical Software Tools, unpublished manuscript, 1985.

Electric Power Research Institute, Technology Assessment Guide (Palo Alto, CA: EPRI, 1978), PS-866-SR.

Ellis, R.P. and M.B. Zimmerman, "What Happened to Nuclear Power: A Discrete Choice Model of Technology Adoption," Review of Economics and Statistics 65, 2 (May 1983) pp. 234-42.

Fox, John, "An Empirical Test of the Averch-Johnson Hypothesis in the Electric Utility Industry," unpublished Ph.D. dissertation, Brown University, 1975.

Fuss, Melvyn, "Factor Substitution in Electric Generation: A Test of the Putty-Clay Hypothesis," in Fuss and McFadden, editors, Production Economics: A Dual Approach to Theory and Applications (Amsterdam: North-Holland Publishing Company, 1978) pp. 187-213.

Gollop, Frank M. and Stephen H. Karlson, "The Electric Power Industry: An Econometric Model of Intertemporal Behavior," Land Economics 56, 3 (August 1980) pp. 299-314.

__________ and Mark J. Roberts, "The Sources of Economic Growth in the U.S. Electric Power Industry," in Cowing and Stevenson, editors, Productivity Measurement in Regulated Industries (New York: Academic Press, 1981) pp. 107-43.

Hausman, Jerry A. and David A. Wise, "A Conditional Probit Model for Qualitative Choice: Discrete Decisions Recognizing Interdependence and Heterogeneous Preferences," Econometrica 46,2 (March 1978) pp. 403-26.

Jeynes, P., Profitability and Economic Choice (Iowa State University Press, 1968).

Joskow, Paul and Frederic S. Mishkin, "Electric Utility Fuel Choice Behavior in the United States," International Economic Review 18,3 (October 1977) pp. 719-36.

__________ and Nancy Rose, "The Effects of Technological Change, Experience, and Environmental Regulation on the Construction Cost of Coal-Burning Generating Units," The RAND Journal of Economics 16, 1 (Spring 1985), pp. 1-27.

Komanoff, Charles, Power Plant Cost Escalation (New York: Komanoff Energy Associates, 1981).

McFadden, Daniel, "Estimation Techniques for the Elasticity of Substitution and Other Production Techniques," in Fuss and McFadden, editors, Production Economics: A Dual Approach to Theory and Applications (Amsterdam: North-Holland Publishing Company, 1978) pp. 187-213.

Moody's Public Utilities Manual (New York: Moody's Investor Service, various years).

Mooz, William E., Cost Analysis of Light Water Reactor Power Plants (Santa Monica: RAND, 1978).

National Association of Regulatory Utility Commissioners, Annual Report on Utility and Carrier Regulation (various years).

Nelson, Randy A., "Regulation, Capital Vintage, and Technical Change in the Electric Utility Industry," Review of Economics and Statistics 66, 1 (1984) pp. 59-69.

__________ and Mark E. Wohar, "Regulation, Scale Economies, and Productivity in Steam-Electric Generation," International Economic Review 24, 1 (February 1983) pp. 57-79.

Petersen, H. Craig, "An Empirical Test of Regulatory Effects," The Bell Journal of Economics 6,1 (Spring 1975) pp. 111-26.

Pomerantz, Lawrence S. and James E. Suelflow, Allowance for Funds Used During Construction (East Lansing, Michigan: Institute of Public Utilities, 1975).

Rothwell, Geoffrey, "A Financial Model of Electric Power Plant Choice," Energy Modeling Seminar, Stanford University (April 12, 1983).

__________ , "Electric Utility Investment under Power Plant Cost Uncertainty," (May 1984). Winner of the Western Economics Association's 1984 Graduate Student Paper Competition.

__________ , "Electric Utility Power Plant Choice Under Investment Regulation," unpublished Ph.D. dissertation, University of California, Berkeley, 1985.

Smithson, Charles W., "The Degree of Regulation and the Monopoly Firm: Further Empirical Evidence," <u>Southern Economics Journal</u> 44, 3 (1978).

Spann, Robert M., "Rate of Return Regulation and Efficiency in Production: An Empirical Test of the Averch-Johnson Thesis," <u>The Bell Journal of Economics</u> 5, 1 (Spring 1974) pp. 38-52.

Stevenson, Rodney, "Measuring Technological Bias," <u>American Economic Review</u> 70, 1 (March 1980) pp. 162-73.

U.S. Department of Energy, <u>Generating Unit Reference File, 1900-1980,</u> Tape Number PB82-150442.

__________ , <u>State Energy Price System</u> (1982), DOE/NBB-0029.

__________ , <u>Projected Costs of Electricity from Nuclear and Coal-Fired</u> Power Plants, (November 1982), DOE/EIS-0356/2.

__________ , <u>Statistics of Privately Owned Electric Utilities in the United States</u> (various years).

U.S. Department of Labor, Bureau of Labor Statistics, <u>Wholesale Prices and Price Indexes</u> (various issues).

Zimmerman, Martin, "Learning Effects and the Commercialization of New Energy Technologies: The Case of Nuclear Power," <u>The Bell Journal of Economics</u> 13, 2 (Autumn 1982), pp. 297-310.