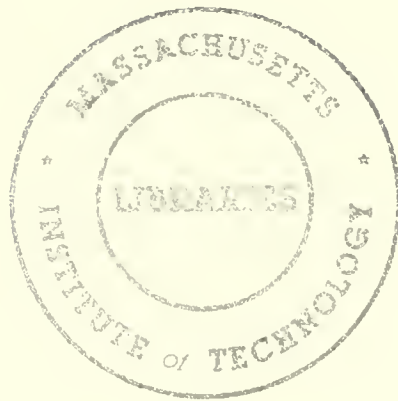WORKING PAPER
ALFRED P. SLOAN SCHOOL OF MANAGEMENT

LEARNING EFFECTS AND THE COMMERCIALIZATION
OF NEW ENERGY TECHNOLOGIES:
THE CASE OF NUCLEAR POWER

by

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#1250-81   November 1981

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Introduction

The process by which new technologies pass from research and development into widespread commercial use has been the focus of much attention in recent years. The proper role of the government in the diffusion process has been at the center of this attention. The issue has been joined in regard to the development of synthetic fuels and the arguments for and against government subsidy to encourage early commercialization of these new technologies.

The policy debate has centered on the wisdom of government subsidy for the construction of large-scale commercial plants. The goal of subsidizing the plants is not to produce new technological information since the technology is already proven. Rather, the goal is to overcome obstacles to the introduction of the technology by the private sector. These obstacles are claimed to be of an informational nature. It is argued there are significant learning externalities. First, observing others' experience leads to lower construction costs. Since the benefits can be realized by another's investment, there is too little incentive to invest.

Secondly, private firms know the technology will work, but they do not know how to accurately forecast the costs. The economics of scale-up are unclear and can only be made clear by the construction of large-scale commercial plants. Only the construction of new commercial-sized plants can clear this up. And further, the whole industry learns from any firm's investments. This logic was behind the effort in the Ford Administration to subsidize through loan guarantees the development of synthetic fuels.

It was the logic behind the establishment of the government-controlled Synthetic Fuels Corporation by the Carter Administration, and presumably it is the logic that prevents the new administration from ending the program (Ref. 12).[1]

Little empirical evidence is available to either support or refute these arguments. This is particularly true for the learning about costs phenomenon. In this paper using nuclear power as a case study, we test for the existence of learning externalities in the early stages of the commercialization process.

From a public policy standpoint there are three issues that bear consideration. Are learning effects present? Secondly, do the learning effects represent nonappropriable benefits such that government subsidy might be theoretically justified?[2] Finally, can we estimate how valuable these nonappropriable benefits might be? The nuclear power industry presents a major example of the research, development and commercialization of a new technology in the energy sector. The early phases of the development were heavily subsidized but the commercialization phase was done largely without government subsidy.[3] Insofar as it was a capital-intensive and complex technology, the experience has relevance to the new generation of energy technology that has been the subject of interest in recent governmental debates.

The analysis of informational externalities in this paper also provides insight as to why early estimation of nuclear power costs were so wrong. The introduction of new technologies calls for engineering estimates of costs. Utility planners had to judge the economic viability of the new technology. These early estimates were typically scaled up from experience with smaller plants. The inherent uncertainty in such a scale-up procedure

is blamed by several observers (see Ref. 4) for the poor performance of the early forecasts of nuclear power costs. We examine this proposition and provide evidence as to the accuracy of the estimation process.

The Introduction of Nuclear Power[4]

The civilian use of nuclear power had its beginnings in the reactor development program of the United States Navy. Under the direction of Admiral (then Captain) Rickover, the Navy pioneered the development of light water reactors. The first attempt to transfer the technology to the private sector was the Industrial Participation Program of the Atomic Energy Commission. This program, begun in 1951, was a modest attempt to involve private firms in studying the feasibility and economic viability of nuclear power.

As a result of this early effort, the AEC became convinced that private firms would not invest in the necessary research and development. In 1953 the AEC decided to direct its own R&D effort toward the construction of a reactor for electricity generation which became the Shippingport project. This was a small (90 MW) light water reactor built by the Duquesne Light Company with AEC subsidy at Shippingport, Pennsylvania. It became operational in 1957. The Shippingport project was owned by the AEC, but Duquesne Light contributed $300 million to the project including the site, the turbine and the generator. Well before completion of the Shippingport project, the AEC announced a major new effort aimed at involving commercial firms in the design, building and operation of experimental reactors. This effort toward nuclear technology transfer was named the Power Reactor Demonstration Program (PRDP).

The AEC announced the first round of the PRDP in 1955. The PRDP went through several different phases with varying degrees of success. The program provided government funding for research and development, while the private participants had to assume the risks of building and operating power reactors. The first-round projects included a pressurized water reactor that was the backbone of the Navy's effort as well as more experimental reactor types. All the projects attempted to solve R&D problems, and only the pressurized water reactor project successfully demonstrated a workable reactor.

The first round gave way to three subsequent rounds. In the second round the focus was on small reactors of an experimental nature. Information about these reactor types was produced, but no technology demonstration was accomplished. Round three and a modified round three dealt with projects ranging from the highly experimental to commercial-sized plants of proven technology. In the latter category were the San Onofre plant of the Pacific Gas and Electric Company and the Haddam plant of the Connecticut Yankee Corporation. These last two reactors were the first large commercial-sized reactors to result from the program. There were no significant research questions that these reactors were to address, and they clearly mark the beginning of the commercialization process. Table 1 lists the first reactor projects, their size and their date of commercial operation.

Interestingly, from the standpoint of commercialization policy, the two government subsidized commercial-scale plants were not yet operating when the utility industry placed numerous orders for large reactors. In 1963 when the San Onfore plant was being ordered, private utilities placed

Table 1

Nuclear Reactors Built between 1953 and 1963

with Government Assistance

Company and Plant	Size (MWe-Net)	Year Contract Awarded	First Year of Commercial Operation
Duquesne Lt. Co. (Shippingport)	90	1953	1957
Commonwealth Edison (Dresden 1)*	200	1955	1960
Consolidated Edison (Indian Pt. 1)	265	1955	1962
Yankee Atomic (Yankee)	175	1956	1961
Pacific Gas and Electric (Humboldt Bay)	69	1958	1963
Philadelphia Electric (Peach Bottom 1)	40	1958	1967
Consumers Power Co. (Big Rock Pt.)	70	1959	1965
Connecticut Yankee (Haddam 1)	575	1962	1968
Dairyland Power Cooperative (Genoa)	53	1962	1969
So. California Edison Co. (San Onofre 1)	430	1963	1968

*This reactor was initially proposed as part of the reactor demonstration program but was eventually built solely with private financing.

Source: The U.S. Atomic Energy Commission, The Nuclear Industry 1973, Wash. 1174-73, 1973.

three orders without subsidy, each plant in excess of 625 MW. In 1965 seven commercial plants were ordered ranging from 330 MW to 873 MW in size. In 1966, 14 utilities ordered 20 units totaling 16,423 megawatts, ranging in size from 457 MW to 1090 MW. The cost of all these plants was borne privately under both fixed-price "turnkey" contracts and the more usual cost-plus contracts.[5]

In summary, the government was intimately involved in the early research and development of nuclear technology. The government also attempted to speed the transfer of the technology to the civilian sector through subsidy. However, large-scale commercial plants were ordered by the private sector before the government subsidized commercial plants were in operation. While valuable information might have been provided by the experimental programs, no large-scale plant experience was available when the technology began to diffuse through the utility industry.[6] Below we ask whether earlier availability of commercial-scale plants would have affected the rate of commercialization. We attempt to answer the question by directly examining the learning experience during the early stages of commercialization and the effect earlier learning would have had on investment decisions.

The Model

Learning accrues from the construction of nuclear power plants. Some learning accrues to the firm constructing the plant and some learning accrues to the industry as a whole. The nature of the learning is twofold. Learning-by-doing in the traditional sense lowers actual construction costs as experience cumulates (Refs. 1, 6). Secondly, as experience is gained, forecasts about costs become more accurate. The greater accuracy comes about as the nature of the scale-up process becomes clear.

The learning effects are estimated from the following model:

$$AC = \alpha_o + \alpha_1 SIZE + \alpha_2 YEAR1 + \alpha_3 LETIME + \alpha_4 LUTIME$$
$$+ \alpha_5 T + \alpha_6 FIRST + \sum_{i=7}^{11} \alpha_i R_i + \alpha_{12} SELFCO$$
$$+ \alpha_{13}\left(\frac{1}{1 + NCONEX}\right) + \alpha_{14}\left(\frac{1}{1 + NINYRS}\right) + \varepsilon_1 \qquad (1)$$

$$(AC-EC) = (\alpha_o - \beta_o) + \alpha_1 SIZE + \beta_1 ESIZE + (\alpha_2 - \beta_2) YEAR1$$
$$+ (\alpha_3 - \beta_3) LETIME + \alpha_4 LUTIME + (\alpha_5 - \beta_5) T$$
$$+ (\alpha_6 - \beta_6) FIRST + \sum_{i=7}^{11} (\alpha_i - \beta_i) R_i$$
$$+ (\alpha_{12} - \beta_{12}) SELFCO + (\alpha_{13} - \beta_{13})\left(\frac{1}{1 + NCONEX}\right)$$
$$+ (\alpha_{14} - \beta_{14})\left(\frac{1}{1 + NINYRS}\right) + \varepsilon_2 \qquad (2)$$

where

AC = The log of actual cost per kilowatt in dollars of 1979

EC = The log of expected cost per kilowatt in dollars of 1979

SIZE = The log of actual size of completed reactor in megawatts

ESIZE = The log of size expected initially for the reactor in megawatts

YEAR1 = Year in which nuclear decision was announced

LETIME = Log of the number of years originally anticipated between
announcement and operation

LUTIME = Log of the difference between actual and anticipated time to
operation

T = A dummy variable with value 1 if plant had a mechanical cooling
tower

FIRST = A dummy variable with value 1 if the generating unit is the
first unit at the plant site, 0 otherwise.

R7 = A dummy variable with value 1 if the plant is in the Mid-Atlantic
Census Region, 0 otherwise

R8 = A dummy variable with value 1 if the plant is in the Midwestern/
East North Central Census Regions, 0 otherwise

R9 = A dummy variable with value 1 if the plant is in the South Atlantic/
East South Central Census Regions, 0 otherwise

R10 = A dummy variable with value 1 if the plant is in the West South
Central and Mountain Census Regions, 0 otherwise

R11 = A dummy variable with value 1 if the plant is located in the
Pacific Census Region, 0 otherwise

SELFCO = A dummy variable with value 1 if the construction was done by
the utility itself

NCONEX = The number of completed plants constructed by the construction
company at the time of the cost estimate

NINYRS = The number of completed plants in the industry as a whole at
the time of the initial estimate of plant cost

$\epsilon_{1,2}$ = Stochastic terms.

Equation (1) captures the effect of learning on actual costs. The two experience variables are (1/1+NCONEX) and (1/1+NINYRS). The variable NCONEX measures the experience of the construction firm. This represents private learning. The NINYRS variable is cumulative industry experience and reflects learning that accrues to individual firms as a result of industry-wide experience. It measures the externality associated with construction activity.[7]

Equation (2) measures the percentage error in the original forecast. This error depends on both the characteristics of the technology and the learning effects. The estimated parameters allow us to examine sources of error in forecasts as well as learning behavior. For example, a comparison of α_1 and β_1 will tell whether misjudgments about economies of scale were responsible for forecast errors. Similarly, α_4 will test the hypothesis that unanticipated delays were responsible for the unexpectedly large costs of nuclear power plants.

Learning is modeled such that its effect reaches a limit as experience gets very large. In the case of both equation (1) and equation (2), cost or cost error begins at a level equal to Ze^{β}, where Z represents the influence of nonexperience variables, and declines to Z as experience gets very large.

The Data

    The variables used in the equations are generally self-explanatory. However, the derivation of both actual and expected cost bears some explanation. The source for actual cost is the total plant cost as reported to the Federal Power Commission (Refs. 14, 15) in the first year of plant operation. It is a total cost figure that sums dollars spent over the entire construction period. As such it is a confusion of nominal dollars of many different years. Similarly, the expected cost is the cost estimate reported to the Atomic Energy Commission (Ref. 13). It too is an estimate in nominal dollars of many years. In the case of expected cost it is an estimate of dollars to be spent over the construction period where the totals include a forecasted rate of inflation. In order to make the two cost variables comparable, each cost must be converted to a constant dollar total.

    The deflation method estimates the proportion of total expenditures that occurs in each year of the construction period and applies the proper deflator for that year. In the case of actual costs, the actual value of the GNP implicit price deflator is used to deflate expenditures. For expected costs we use the 10-year bond rate on U.S. Treasury securities as a measure of the expected rate of inflation over the expected construction period. The proportion of total expenditure that occurs in any given year is taken from data on the typical cash flow for a nuclear project (Ref. 3). Finally, in both cases we remove the interest paid during construction on the borrowed funds so that the cost variables represent actual or estimated outlays on labor, equipment and materials. The details of the deflation process are explained in Appendix 1.

The other variables come from several sources. Data on the expected size, the year of announcement, the year of expected commercial operation, are taken from data reported to the Atomic Energy Commission (Ref. 13). The size of the completed plant, the year of completion, are reported in data submitted to the Federal Energy Regulatory Commission (Refs. 14, 15). The tower variable is from an annual survey by McGraw-Hill of nuclear plants (Ref. 7). The sample consists of the 41 nuclear plants completed between 1968 and 1980 for which completed cost figures are available.

Estimation and Results

Equations (1) and (2) are estimated jointly using Zellner's iterative Generalized Least Squares. The use of GLS is warranted since the disturbance in actual costs reflects unobserved variables that will also affect expectations about cost. The results are presented in Table 2.

Table 2

Regression Results

Parameter/Variable	Parameter Estimate	Standard Error	t-Statistic
Equation (1)			
α_o/constant	-2.33	2.58	-.91
α_1/SIZE	-.17	.13	-1.33
α_2/YEAR1	.11	.04	2.79
α_3/LETIME	1.02	.23	4.40
α_4/LUTIME	.13	.07	1.84
α_5/T	.14	.06	2.46
α_6/FIRST	.27	.06	4.31
α_7/R7	-.02	.12	-.20
α_8/R8	-.33	.10	3.29
α_9/R9	-.36	.10	3.62
α_{10}/R10	-.50	.18	-2.76
α_{11}/R11	-.16	.15	-1.05
α_{12}/SELFCO	-.25	.06	-3.89
$\alpha_{13}/\frac{1}{1 + NCONEX}$	.46	.08	5.72
$\alpha_{14}/\frac{1}{1 + NINYRS}$	.25	.15	1.66
Equation (2)			
$\alpha_o - \beta_o$/constant	-3.24	3.53	-.92
β_1/ESIZE	.35	.11	3.20
$\alpha_2 - \beta_2$/YEAR1	.007	.05	.12
$\alpha_3 - \beta_3$/LETIME	1.08	.29	3.69
$\alpha_5 - \beta_5$/T	.17	.08	2.14

(Continued)

Table 2

(Continued)

Parameter/Variable	Parameter Estimate	Standard Error	t-Statistic
$\alpha_6 - \beta_6$/FIRST	.20	.09	2.37
$\alpha_7 - \beta_7$/R7	−.07	.16	−.44
$\alpha_8 - \beta_8$/R8	−.27	.14	−1.97
$\alpha_9 - \beta_9$/R9	−.19	.14	−1.37
$\alpha_{10} - \beta_{10}$/R10	−.68	.25	−2.72
$\alpha_{11} - \beta_{11}$/R11	−.19	.21	−.89
$\alpha_{12} - \beta_{12}$/SELFCO	−.36	.09	−4.05
$\alpha_{13} - \beta_{13}/\dfrac{1}{1 + \text{NCONEX}}$	.36	.11	3.27
$\alpha_{14} - \beta_{14}/\dfrac{1}{1 + \text{NINYRS}}$	.46	.21	2.16

Log of likelihood function = 45.9023.

Number of obs = 41.

Why were the cost estimates wrong?

a. Economies of scale and other technology-related factors

A favorite explanation for the miscalculation of costs was that the early cost estimates were based upon an incorrect understanding of the economies of scale. All initial estimates for new technologies are based upon scale-up from smaller-scale plants. Estimates of equation (2) suggest that this was a factor, but by no means the most important source of error. The expected scale parameter, β_1, is estimated to be twice the actually realized factor, α_1. However, the relatively large standard error associated with the actual scale parameter does not allow rejection of the hypothesis of equality. A second technology-associated item is the presence of a mechanical cooling tower. These towers increased cost estimation errors on average by 18% as measured by $(\alpha_5-\beta_5)$. It appears that lack of understanding of the basic technology did contribute to cost error.

b. The effect of delays

In all discussions of the costs of nuclear power a large importance has been attributed to long lags in construction. This is confirmed by our estimates. Doubling the planned construction period, ETIME, more than doubles the real cost of the plant as measured by α_3. Unanticipated delays, as measured by α_4, also positively affect costs although their effect is estimated to be much less important.

The actual effects of delays were quite different than anticipated. The estimate of $(\alpha_3-\beta_3)$ in equation (2) suggests that the effect of delay on cost was not taken into account in forming initial estimates of cost. We cannot reject the hypothesis that $\beta_3 = 0$. In other words, at the time of the initial forecast, a utility felt the anticipated construction period would have little effect on cost. This is not totally unreasonable since

if a delay were anticipated, expenditures could be planned to mitigate
unfavorable consequences on cost. For example, licensing delays, if
anticipated, just postponed initial expenditures. The bulk of the expected
cost impact of delays would be on interest during construction, and it has
been taken out in the deflation process.

The value of β_3 implies, however, that expectations were for constant
factor prices. Actual costs, as measured by α_2, were increasing by 11 per-
cent per year in real terms. Apparently, forecasters were aware of this
development and increased their estimates by the same amount since $\alpha_2 - \beta_2$
is essentially zero. Yet they did not extrapolate the 11 percent per year
increase forward. Their estimated cost reflected previous developments, but
assumed no further change in the future. Since anticipated lags had no
effect on anticipated cost, they must have assumed that real factor prices
as well as regulatory requirements would be constant. This is a static
expectation formulation process. Each year the initial cost estimate was
increased, but continuing cost increases were not extrapolated out into the
future. The combination of new regulations and real factor price increases
we infer, therefore, were a continual "surprise."

Learning Effects

a. Learning-by-doing

The results presented in Table 2 suggest significant effects for all types of learning discussed above. Learning-by-doing results in cheaper construction. This learning-by-doing is partially internalized by the construction firm and it partially accrues to the industry as a whole.[10] The internalized portion as measured by α_{13} is estimated to be almost twice as large as the external learning measured by α_{14}. The coefficient for internalized learning, α_{14}, is significantly different from zero at over a 99.9 percent level of confidence. The precision of the estimate of the coefficient measuring external learnings is not as good. The coefficient is significantly different from zero at about a 95 percent level of confidence using a one-tailed test.

There is a potentially large bias in the estimate of internalized learning effects. A construction firm with a great deal of experience can capture rents. Such a firm can charge the price of its competitors and realize the lower cost as profit. The utility is not without bargaining power and a likely outcome is a sharing of the rents.

Possible measures of this rent are the coefficients of SELFCO. That variable measures whether or not utilities doing their own construction were more successful in constructing plants and estimating costs. The answer to both questions appears to be yes. On average, those utilities that built their own plants realized a savings of 25 percent and were 36 percent more accurate in their cost estimation.[11] This could reflect savings due to a

better managerial arrangement, or it could be a reflection that in these cases the utility captured the entire rent. In any event, private learning appears important in the early days of technology introduction.

We can put the externality associated with learning-by-doing into context by examining how additional plants available in 1965 would have affected the future development of costs given actual investment decisions. Table 3 presents the actual number of plants completed in each year. We then ask how much lower costs would have been if additional plants had been available earlier.[12]

A single plant built by 1965 would have had a nontrivial effect as seen in column (3) of Table 3. The marginal benefit of other plants was small. A single plant reduces the cost not only of the next plant, but of all future plants. Therefore the total value of learning depends on the number of plants built and the discount rate. Further, we have modeled learning as occurring in a multiplicative fashion. For example, experience that saves 15 percent of labor input has an absolute value that depends on the cost of labor. Finally, since knowledge of what learning will be affects investment decisions, a complex model is needed to calculate the value of learning.

Our objective here is much more limited. We want only to approximate the value of this learning. The policy issue we address is whether the externality justifies large subsidy of the early commercial plants. Therefore, we examine the value of the externality given expectations about future costs as of 1965. We assume, for simplicity, that the actual schedule of nuclear plant completion was known. We then ask, given our estimates of the learning effects, what the expected value of the external learning would have been. At a 5 percent rate of discount the learning

Table 3

The Effect of Additional Plants Available on Learning by Doing

(1)	(2)	(3)				
Year	Cumulative number of plants completed	Incremental percentage reduction in cost with additional plants				
		1	2	3	4	5
1968	1	13.5	4.3	2.2	1.2	.9
1969	3	4.3	2.2	1.2	.9	.6
1970	4	.9	.6	.5	.3	.3
1971	5	.3	.3	.2	.1	.1
1972	10	.1	.1	.1	.1	.1
1973	19	neg	neg	neg	neg	neg
1974	31	neg	neg	neg	neg	neg
1975	42	neg	neg	neg	neg	neg
1976	50	neg	neg	neg	neg	neg
1977	55	neg	neg	neg	neg	neg

Source: Columns (1) and (3), calculations using equation (1).

   Column (2), Mc-Graw-Hill (Ref. 7).

associated with the first plant would have had an expected total value

equal to 29 percent of the 1966 cost of a plant. The externality associated

with the second plant would have been 15 percent of the initial plant cost,

and for the third plant the learning would have been equal to 9 percent of

initial cost.[13]

b. Learning about costs and the rate of commercialization

The estimated parameters indicate that there was, in fact, signif-

icant learning about costs. Approximately half the information was captured

by the firm and half was a benefit to all firms in the industry. Again, the

external information provided by additional plants declines rapidly. The

first plant leads to 26 percent reduction in the cost error in the next

plant. The second plant reduces error in the third by 8 percent, and the

third reduces error in the fourth by 4 percent. This improvement in forecasts

comes about both because expected costs increase and because actual costs

decrease.

There is a seemingly puzzling result. Private learning about costs as

measured by β_{13} (= .10)   lowers cost estimates, and public information as

measured by β_{14} raises cost estimates since β_{14} is negative (= −.21).

In fact, these estimates are consistent. Private learning leads to lower

actual costs as measured by α_{13} . This learning should be taken into

account in formulation of new cost estimates. The private learning should

also lead people to realize that they have been underestimating costs. Thus,

the private effect of completing a plant for a company would be to first

lower their expectation of cost because now they know they build plants

more cheaply. They should also adjust for the downward bias in their early

estimates by raising their estimate for new plants. The two factors work

in opposite directions. The net effect depends on the relative strength of each type of learning. Their estimated cost could rise or fall, but the net effect should be to lower cost estimation errors. This is in fact what the results suggest, as measured by $\alpha_{13} - \beta_{13}$.

Public learning has a relatively smaller impact on actual costs as measured by α_{14}. The companies thus first lower estimated costs to reflect the fact that now they build more efficiently. They also adjust for the bias in earlier estimates. Again the net effect is to lower cost errors. To compare β_{13} and β_{14}, the parameters that we thought should have been symmetric, only compares which type of learning, learning to build more efficiently or correcting for bias in estimates, is stronger. The estimates in equation (2) of $\alpha_{13} - \beta_{13}$ and $\alpha_{14} - \beta_{14}$ are the amount the error is reduced by private and public experience respectively. The results suggest that learning about previous cost underestimates is about equal for private and industry-wide experience.[14]

To put learning about costs into context, we ask how decisions would have been altered if additional plants and the information they bring about costs had been available earlier. The effect of learning on commercialization works only through its effect on expectations. Investment decisions are based on expected costs. We concentrate here only on the externality associated with learning about cost, since the private information would have been taken into account in investment planning.

Assume that utilities were expected cost minimizers.[15] The utilities were choosing between nuclear power and the best fossil-fuel alternative. In most cases the alternative was coal power.[16] We characterize their decision rule with respect to technology adoption as follows.

Let $N = 1$ indicate a nuclear choice. Then $N = 1$ if:

$$\frac{X_N \epsilon_N}{X_C \epsilon_C} < 1 \tag{3}$$

(3)

$N = 0$, otherwise

where

X = fuel, operating and maintenance and capital cost in $ per Kwhr of generation

ϵ = unobserved factors affecting cost

N, C = subscripts denoting nuclear, fossil respectively.

Equation (3) can be interpreted in the following way. Utilities will choose the cheapest generation alternative. Part of the cost of generation is observed capital, fuel, and operation and maintenance cost. Another part of the cost cannot be observed by an analyst. For example, the perceptions of the utility about public acceptance of a nuclear plant might significantly influence choice, yet is generally unobservable. Site-specific items that are not easily observed might affect desirability of one technology or another. Thus ϵ_C and ϵ_N will be known to the utility, but will not in general be known by the researcher examining the behavior of the utilities. For any given set of observed fuel, capital, operation and maintenance there is therefore a probability between zero and one that the utility in question would choose nuclear power.

Assume that $\log \epsilon_C$, $\log \epsilon_N$ are normally distributed with zero mean. Thus $\log \epsilon$ is also normally distributed with zero mean. The probability of any individual utility choosing nuclear power is simply:

$$P(N=1) = 1 - \int_{-\infty}^{\log X_N - \log X_C} \frac{1}{\sigma} \phi \left(\frac{\log \varepsilon}{\sigma} \right) d \log \varepsilon$$

where ϕ is the standard normal distribution. Learning provides new information about X_N, altering the probability of choosing nuclear power. In the present case, the new information raises expected capital cost and thus X_N. This lowers the probability of a nuclear choice. To calculate the effect of this learning we need estimates of fuel and operating costs for both types of plants. We need capital cost for a coal plant as well as capital cost for a nuclear plant before and after additional plants are completed. We also need an estimate of σ. Estimates of the cost items are summarized in Table 4. We use our estimates of learning to calculate how nuclear cost estimates would have changed with additional construction. All that remains to be estimated is σ.

We estimate σ in the following way. We take historical data on the proportion of plants ordered in 1966-1970 in the Midwest as a measure of the probability of choosing a nuclear plant in that region. We then take the average values of the costs of nuclear power generation and of coal generation in the Midwest for the same period. We solve for σ using the following equation:

$$U_p = \frac{(\log X_C - \log X_N)}{\sigma} \tag{4}$$

where U_p – the point on the standard normal distribution that corresponds to the proportion of nuclear power plants actually chosen.

Using the estimated value of σ (= .32), we calculate how information about increased costs would have altered the proportion of nuclear plants chosen. We assume that σ is equal in all regions. The results are shown in Table 5. In 1966-1970, nuclear power maintained an average expected

Table 4

Comparative Expected Costs of Coal and Nuclear Power in the Midwest, 1965-1970
(mills per KWhr)

	Coal Costs				Nuclear Costs			
Year	Capital	Operation & Maintenance	Fuel	Total	Capital	Operation & Maintenance	Fuel	Total
1965	1.60	.3	2.4	4.30	1.76	.4	1.58	3.74
1966	1.63	.2	2.4	4.23	1.87	.2	1.38	3.45
1967	1.67	.4	2.4	4.47	2.07	.7	1.38	4.15
1968	2.04	.4	2.5	4.94	2.48	.7	1.46	4.64
1969	2.44	.4	2.6	5.44	2.91	.7	1.54	5.15
1970	2.73	.4	3.0	6.13	3.34	.7	1.62	5.66

Sources and Notes

1. Capital costs for coal as well as nuclear come from the following sources. We take the midpoint esimate. We use these sources for nuclear since they use representative values of all the exogenous variables in our estimating equations as well as the interest during construction. They also are comparable to the coal estimates.

   1965: Ref. 5
   1966: Refs. 5, 11
   1967: Ref. 5
   1968: interpolated between 1967 and 1969
   1969: Ref. 11
   1970: Ref. 16

   We assume an 80 percent operating rate, which was the expected operating rate in those years, and a 10 percent annual capital charge rate. Cost in mills per KWhr is
   $[1000 \times (\$1 \text{ KW}) \times .10]/[(8760 \times .8)]$.

2. Operation and maintenance costs as well as nuclear fuel costs are from the same sources as above.

3. Coal prices are average as-burned cost for Illinois as reported in Ref.   .   The heat rate, or Btu/KWhr, is assumed to be 10,000.

Table 5

The Effect of Additional Plants Available in 1965

on Later Nuclear Decisions

Number of Plants	Perceived Cost Advantage for Nuclear 1966-70 Average (%)	Incremental Reduction in Nuclear Decisions	
		(%)	(MW)
1	7	3.5	3980
2	6	1.2	1365
3	5	1.2	1365

advantage of 10.2 percent over coal power. Had a single plant been built
by 1965, the expected advantage would have been reduced to 7 percent. This
would have decreased the estimated probability of choosing a nuclear power
plant by 3.5 percent. The expected change in nuclear power construction
would have been 3980 MW, or about four fewer plants in the 1966-1970 period.
Two commercial-sized plants would have resulted in total probability change
of 4.7 percent. Thus, the second plant would have had an incremental effect
of approximately 1.2 percent. In other words, the rate of learning was too
small relative to expected costs to materially affect the rate of commercial-
ization.[17]

Summary and Conclusions

We have estimated the learning that occurs during the early stages of
the introduction of a new technology. In the case of nuclear power,
experience gained from the construction of the first few plants led to
lower costs and better cost estimates. Some of the learning accrued to
the industry as a whole and therefore was an externality. However, the
externality was small and largely associated with the first completed
commercial-sized plant.

The learnings-about-cost phenomenon was also present. About half the
learning about costs represented an externality. However, learning was
too small relative to the initial expected cost differential to have much
of an influence on the rate of commercialization. A large number of
nuclear plants were ordered without the benefit of experience with
commercial-scale plants. Had the government built or subsidized earlier
construction, there would have been only a slight effect on the future
rate of commercialization. Since investment behavior would have been

similar with or without subsidy, the value of the information was small.

The results here are limited to the early experience with nuclear power. The results cannot be generalized to other technologies. However, it does suggest that claims of large learning effects for new synthetic fuel technologies would represent dramatically different behavior than that for a recent and important case of new technology diffusion.

Footnotes

1. The Carter program was an expansion of an earlier program proposed by the Ford Administration. See Ref. 12.

2. Richard Schmalensee correctly argues that the presence of externalities alone does not justify government support of synthetic fuels technology. The issue is rather one of whether the payoff to government subsidy is larger in synthetic fuels than in any other technology. The evidence in this paper should be regarded as contributing to the general question of whether there are significant learning effects in the early stages of commercialization. See Ref. 10.

3. We use the distinction that has become commonplace between demonstration of the technical feasibility on a pilot plant basis and the building of commercial-scale plants once the technology has been demonstrated.

4. This discussion relies heavily on the description in Allen (Ref. 2).

5. Turnkey contracts were fixed price contracts whereby the reactor vendors agreed to deliver an entire plant at a fixed price.

6. Bupp and Derian (Ref. 4) stress this point as an explanation for the errors involved in forecasting initial power plant costs.

7. One is added to the denominator to allow us to treat the case where there is no experience. The NCONEX variable includes turnkey plants, yet the industry experience variable, NINYRS, excludes turnkey experience. This was done since an individual firm can be expected to learn from experience on a turnkey plant, yet the industry as a whole does not observe true costs for a turnkey plant.

8. There is an issue as to whether these estimates were believed. There
    appears to be no reason why in reporting the expected cost a utility
    would be biased one way or another. The cost estimate typically was
    reported in a prospectus or to a regulatory commission. Low estimates
    would enhance the acceptance by the financial community, but ultimately
    make the utilities look incompetent when they asked the regulatory
    commission to include the actual cost in the rate base.

    There is a possible statistical reason for the underestimation
    bias. We observe the costs of nuclear plants actually built. For
    these plants, the utility decided that costs would be cheaper than for
    all alternatives. Therefore, it is possible that those plants that are
    built are, on average, those for which costs are underestimated. It is
    unlikely that this would explain the underestimate for each plant in the
    sample. Furthermore, this provides no explanation for the systematic
    relationship of bias, as measured by equation (2), to experience.

9. The null hypothesis that $\beta_2 = \alpha_2$ cannot be rejected at any reasonable
    level of confidence.

10. This conflicts with earlier results by Mooz (Ref. 8). The reason is
    the different variables used by Mooz and the present paper to measure
    experience. Mooz cumulates the number of plants beginning with the
    year in which the construction permit was issued. We use the completion
    date as a measure of experience.

11. The 36 percent greater accuracy is, of course, attributable in large
    part to their lower realized costs. Expected costs were only 11 percent
    higher than for plants not built by the utilities.

12.   The exoponential form, while a reasonable specification forces a
       pattern of decline in benefits. To check the reasonableness of this
       specification a piecewise linear equation was run where there were
       separate dummy variables for the first plant built and the second
       plant built in the industry. The results confirm the rapid decline
       in external learning. Forecasts were 17% better after the first
       plant and an additional 4% better after the second plant. Actual
       costs were 15% lower after the first plant. However, after the second
       plant costs, under any reasonable significance level, appear not to be
       different than the initial level.

13.   We express cost as a percent of initial cost since future cost
       developments were not anticipated as the results above suggest.

14.   I am indebted to Rodney Smith for discussion on this issue.

15.   This assumes that the individual project will not affect price.
       For a full-scale estimation of such a model, see Zimmerman and Ellis
       (1980).

16.   Oil was an alternative for baseload generation primarily on the East
       and West coasts. Our estimates below are all for the Midwest where
       coal was the only alternative to nuclear power.

17.   The irony here is that more knowledge about true costs would have
       resulted in fewer plants being built. Proponents of subsidies for
       synfuels see it as a way of expanding the role of the technology.

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Appendix 1

Deflation of Reported Cost

The reported cost, R, is the sum of all expenditures including interest during construction denominated in dollars of the year of expenditure. Let Z be the cost in constant dollars excluding interest during construction. Let P_t be the proportion of Z spent in year t. Let $r(t)$ be the nominal interest rate, $i(t)$ the rate of inflation in year t, and T the entire construction period. Then,

$$R = \sum_0^T P_t Z \prod_0^t \left(1 + i(t)\right) \prod_{t+1}^T \left(1 + r(t)\right)$$

or

$$Z = \frac{R}{\sum_0^T P_t \prod_0^t \left(1 + i(t)\right) \prod_{t+1}^T \left(1 + r(t)\right)} \tag{1}$$

For expected cost, $i(t)$ is taken to be the 10-year Treasury bond rate and $r(t)$ is taken to be the interest rate being paid on long-term debt for utilities receiving the same Moody's bond rating as the utility in question. Both are taken for the year of announcement of the plant. When actual costs are deflated, $i(t)$ is the actually realized inflation as measured by the GNP implicit price deflator and $r(t)$ actual rates as measured by the average rate reported by the Energy Information Agency in <u>Statistics of Privately Owned Electric Utilities in the United States</u>.