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Theory and Evidence for Using the Economy-of-Scale Law in Power Plant Economics

Doan L. Phung

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A04 Microfiche A01

ORNL/TM-10195

THEORY AND EVIDENCE FOR USING THE ECONOMY-OF-SCALE LAW IN POWER PLANT ECONOMICS

by
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Date Prepared — October 1986
Date Published — May 1987

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Report Prepared by
PAI Corporation
P. O. Box 1135
Oak Ridge, Tennessee 37831

under
Subcontract 12X-79356V

for

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

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ABSTRACT

This report compiles theory and evidence for the use of the economy-of-scale law in energy economics, particularly in the estimation of capital costs for coal-fired and nuclear power plants. The economy-of-scale law is widely used in its simplest form: cost is directly proportional to capacity raised to an exponent. An additive constant is an important component that is not generally taken into account. Also, the economy of scale is perforce valid only over a limited size range.

The majority of engineering studies have estimated an economy of scale exponent of 0.7 to 0.9 for coal-fired plants and an exponent of 0.4 to 0.6 for nuclear plants in the capacity ranges of 400 to 1000 MWe. However, the majority of econometric analyses found little or no economy of scale for coal-fired plants and only a slight economy of scale for nuclear plants. This disparity is explained by the fact that economists have included regulatory and time-related costs in addition to the direct and indirect costs used by the engineers. Regulatory and time-related costs have become an increasingly larger portion of total costs during the last decade. In addition, these costs appeared to have either a very small economy of scale or to be increasing as the size of the power plant increased. We conclude that gains in economy of scale can only be made by reducing regulatory and time-related costs through design standardization and regulatory stability, in combination with more favorable economic conditions.

1. EXECUTIVE SUMMARY

The question of optimum size, whether it relates to a power plant, a piece of equipment, or a new technology, is an economic one that has far-reaching implications. If a larger power plant or piece of equipment can be built and operated at lower cost per unit, we have gains in overall productivity that are essential to an improved standard of living.

Nuclear power plants showed economy of scale as they progressed from the small demonstration plants to larger operating units in the 200-600 MWe range of the 1950s and 1960s. However, when even larger units built during the 1970s showed a leveling off or a reversing of the trend in economy of scale, one is concerned with the causes and the future competitiveness of the various power options in the coming decade. The purpose of this report is to examine the theory and evidence for using the economy-of-scale law in power plant economics.

1.1 THEORY

It is widely observed and accepted in engineering that the cost of a piece of equipment is not directly proportional to its capacity; rather the proportionality is through the power law:

$$K = a + bY^n$$

where $\underline{K}$ is the cost, $\underline{Y}$ is the capacity, $\underline{a}$ and $\underline{b}$ are constants, and $\underline{n}$ is the scale exponent. The relative value of the constant $\underline{a}$ with respect to $\underline{K}$ can be very important in the ratio of the costs for two power plants of different sizes. In addition, economy of scale is valid only over a limited range; it is questionable that an empirical law with fixed constants can be valid over a wide range as, for example, from 100 to 1300 MWe.

Engineers have traditionally looked at the forward, or prospective, or "bottom up," structure of the costs in estimating the scaling exponent $\underline{n}$, while economists have customarily looked at the overall costs retrospectively. As the overall costs have included several social, regulatory, and economic elements and have become an increasingly larger portion of total costs during the 1970s and early 1980s, economy of scale has become less evident.

1.2 EMPIRICAL EVIDENCE

Empirical data on process equipment, large electric equipment, power plants, and operations and maintenance of power plants were examined to determine the extent to which the economy-of-scale law holds true.

In process equipment, Phung et al.[2] found that the scale exponent n changes from a low of 0.52 for centrifugal pumps and drivers to a high of 0.85 for process furnace and direct boilers. Lee's study[3] shows that economy of scale exists in large electric equipment (steam turbine generators, power transformers, high voltage direct conversion equipment, and transmission lines) over their technological ranges.

Literature searches revealed eight empirical studies dealing with the economy of scale in fossil-fired and nuclear power plants. The majority of the engineering studies estimated a scale exponent of 0.7 to 0.9 for coal-fired plants and an exponent of 0.4 to 0.6 for nuclear plants in the capacity ranges of 400 to 1000 MWe. A scale exponent of about 0.85 was suggested by a study for fossil-fired plants between 100 and 400 MWe, but no similar value was available for nuclear plants. It was widely believed, however, that the economy of scale for nuclear plants in this range is very pronounced, for example, more saving as n becomes smaller. (Note that when comparing unit cost in $/kWe, the exponent n is transformed into another exponent, s, with s = n-1).

The majority of econometric analyses in the literature found little or no economy of scale for coal-fired plants and only a slight economy of scale for nuclear plants. In other words, the cost of a nuclear plant in $/kWe declined only slightly as the plant size increased.

Studies dealing with economy of size of electric utilities found that the unit cost exponent s varies across company lines and that the cost of generation also depends on the size of the generating unit. Christiansen and Greene[14] held that the economy of scale for electric utilities is steepest at the small-size end, becomes level for a wide range, and then reverses at the very large sizes. Huettner and Landon[15] and Seitz[16] indicated similar findings, showing that a small number of extremely large firms may exhibit diseconomy of scale.

With respect to fuels, the economy of scale is relatively small ($n \approx 1$) for coal but could be large ($n < 1$) for nuclear fuel. This is attributed to the fact that the nuclear fuel cycle cost involves components such as transportation and expert services which do not depend on the size of the reactor. Therefore, per unit capacity cost can be very large for smaller capacity.

Myers et al.[18] found little or no dependence of the number of plant personnel on the size of the generating units in the range of 800 to 1200 MWe. Factors such as regulatory requirements, quality assurance, and age of the plant have predominated. This leads to more expensive staffing costs per unit capacity in the smaller capacity reactors.

1.3 USE OF ECONOMY OF SCALE

Since the early 1970s, United Engineers and Constructors, Inc., (UE & C) has been doing cost estimates for hypothetical power plants of various fuel types, including uranium, coal, oil, and natural gas. The work has been supported by the Department of Energy and the Nuclear Regulatory Commission and their predecessors. A series of reports has been published, the latest of which is DOE/NE-0051 (August 1985). Information in these reports constitute a major basis for the CONCEPT code which is compiled and maintained by Oak Ridge National Laboratory.

The approach used by UE & C includes defining the design basis, fixing certain standards and regulations, using current material and price data, and estimating the "overnight" cost of a power plant.

Other agencies, vendors, and architect-engineers have used the economy-of-scale law in their cost estimates of power plants. Several observations can be made from review of their cost-size scaling: the economy of scale is more pronounced for nuclear plants than for coal-fired plants; economy of scale is more pronounced in the lower rating range (100-400 MWe) than in the higher rating range (400-1300 MWe); and as regulations became more stringent for building and operating a nuclear plant in the 1970s, economy of scale disfavored small reactors. This later observation was confused by the fact that large power plants in the 1970s also took a long time to build during which the escalation and interest costs drastically increased, thus increasing the overall cost of the completed facility.

1.4 CONCLUSIONS

Economy of scale depends on many factors. Artisans and technologists have traditionally built prototypes to verify the workability of an idea. If the prototype does not work, the idea is modified or abandoned; if it does, then bigger and better devices are built based on the prototype.

In the power plant sector, economy of scale made possible the increase in plant size over the 1950s and 1960s. However, when plant sizes increased beyond 1000 MWe in the 1970s, the point of diminishing return was passed. There are several components to the final cost of a power plant, including direct, indirect, and value and time-related costs. The latter have assumed a larger fraction of total costs over time.

The 1970s were a turbulent era when the environmental and safety requirements on power plants were increased even during plant construction, when inflation and interest rates were high, and when the construction durations became longer than estimated by a factor of two to three times, particularly for larger power plants. In the future, as power plants become more standardized and regulation more stabilized, we expect that the time-related cost components will decrease and the economy-of-scale law will once again be significant in power plant economics.

2. THEORY ON THE ECONOMY OF SCALE

2.1 AN EXPERIENCE-BASED LAW AND ITS LIMITATIONS

It is widely observed and accepted in engineering that the cost of a piece of equipment is not directly proportional to its capacity, but rather to that capacity raised to an exponent n:

$$K = a + b\,Y^n \qquad (1)$$

where K is the cost, Y is the capacity, a and b are constants, and n is the scale exponent.

The above observation has a technical basis in that the cost is proportional to the area while the capacity is proportional to the volume. As the volume doubles, the surface should increase by a factor smaller than two. In other words, the equipment can do twice as much for a cost less than double — hence the term "economy of scale."

Acceptance of economy of scale frequently assumes that the technology for both the smaller and the larger equipment is the same. If the larger unit also incorporates improved manufacturing methods (as is frequently the case because the larger unit is almost always developed after the smaller unit), then the economy of scale is even better than ordinary. If the larger unit runs into some physical constraints (e.g. material strength, fabrication limitations), then the economy of scale could slow down or even reverse. Thus, one should expect that a "cost versus capacity" curve should be only "piecewise" valid. In other words, there is a different value of n for different ranges of Y.

In power plant economics it is easier sometimes to compare the relative costs of two plant sizes by the unit capacity cost. Let $U = K/Y$ be the unit capacity cost, say in dollars per kilowatt of installed capacity ($/kW), then equation 1 can be modified as follows:

$$U = U_0 + b'Y^{n-1} \qquad (2)$$

where U_0 and b' are new constants.

Equation 2 can also be written

$$\frac{U_2 - U_{0,2}}{U_1 - U_{0,1}} = \frac{b'_2}{b'_1}\left(\frac{Y_2}{Y_1}\right)^{n-1} \qquad (3)$$

The above equation illustrates several properties of the economy of scale:

1. Only when $U_{0,2} = U_{0,1} = 0$ and $b'_2 = b'_1$ can one have the economy- of-scale law in its simplest and most frequently used form,

$$\frac{U_2}{U_1} = \left(\frac{Y_2}{Y_1}\right)^{n-1} \quad (4)$$

2. If $U_{0,2} \neq U_{0,1}$ and both are of significant magnitude with respect to U, then an attempt to determine the scale exponent n without the knowledge of these constants can lead to significant misinformation. The same conclusion can be drawn when $b'_2 \neq b'_1$.

The following numerical example illustrates the case in point: A power utility was told that a 800-MWe power plant would cost \$1500/kW to build while a 1200-MWe plant would only cost \$1300/kW to build. At the simplest level of reasoning, the economy of scale is determined from equation 4,

$$n = 1 + \ln (1300/1500) / \ln (1200/800) = 0.65.$$

If the utility is also told, however, that no matter what size plant it decides to build, the regulatory and owners' cost throughout the duration of construction is \$200/kW, then the scale factor would be determined through equation 3, assuming $b'_2 = b'_1$,

$$n = 1 + \ln (1100/1300) / \ln (1200/800) = 0.59.$$

If for reasons such as longer construction time and higher investment risk, the company incurs $U_{0,2}$ = \$400/kW instead of \$200/kW, then the scale exponent n is

$$n = 1 + \ln (1100/1100) / \ln (1200/800) = 1.$$

The above example illustrates the fact that only in the most stable technological, economic, and regulatory environment can the economy-of-scale exponent be determined with confidence. When there are complications, such as in the turbulent 1970s, the values of U_0 and b' and other influencing factors tend to render a specific value of n meaningless.

2.2 COMBINING THE SCALE EXPONENTS OF SEVERAL COMPONENTS

A power plant consists of several plant components each of which may have a different economy of scale. Understanding these various components and their economies of scale and contribution towards the overall plant is also important to resolving the discrepancy between prospective and retrospective views of the effect of plant size on power plant economics.

Let K be the plant cost for plant capacity Y, K_{Ref} be the reference plant cost for the reference capacity Y_{Ref}, and K_j and $K_{Ref,j}$ be plant component and reference plant component costs, respectively. Then

$$K = \sum K_j \quad (5)$$

$$K_{Ref} = \sum K_{Ref,j}. \quad (6)$$

Let M_j be the fraction of component plant cost with respect to overall plant cost. Then

$$M_j = K_j/K \quad ; \quad \sum M_j = 1. \tag{7}$$

Note that each K_j has a different scale exponent n_j with respect to $K_{Ref,j}$ and that M_j may change for various design and construction situations. In the simplest form of the economy of scale expressed in equation 4, equations 5 and 6 can be written

$$K/K_{Ref} = (Y/Y_{Ref})^n = 1 + n \ln (Y/Y_{Ref}) + \ldots \tag{8}$$

$$\sum K_j/K_{Ref} = \sum M_j (Y/Y_{Ref})^{n_j} = \sum M_j + \sum M_j n_j \ln(Y/Y_{Ref}) + \ldots. \tag{9}$$

Equating equations 8 and 9 using only the first two terms and the property of equation 7, one has

$$n = \sum M_j n_j. \tag{10}$$

Thus, in the simplest form of the economy of scale law, ignoring secondary factors, the scale exponent of the power plant is the sum of the scale exponents of the components, each of which is weighted with the cost fraction of the component with respect to the overall plant.

Comtois[1] has used the equation 10 to explain the flattening of the economy of scale (increasing value of n) for power plants during the 1970s. During this period, because of regulatory requirements, double-digit inflation, double-digit interest rates, and long construction times, the fraction M_j of time-related costs has increased drastically, from around 15% to as much as 60% of the final cost. Since the carrying charge is directly proportional to the amount borrowed and since the borrowed amount includes a large component that is size independent ($n = 1$), the increase in its fraction results in increasing the value of n — hence a flattening in the economy of scale.

Table 2.1 illustrates the value of n for two cases. In Case 1 the financial component represents only 15% of the total capital cost at the time of start of operation. In Case 2 the financial component represents 50% of the total capital cost at the time of start of operation. In spite of the assumed similar economy of scale of corresponding plant components, the overall exponent scale of Case 2 is 0.760 while of Case 1 is 0.554.

3. EMPIRICAL EVIDENCE

There are innumerable examples in daily life that a bigger utensil, piece of equipment, or device (a house, a range, a truck, a coal miner, or a ship) costs less per of unit capacity than a smaller one. Between 1940 and 1965 as the demand for electricity was growing, larger and larger generating plants were built at a lower and lower real cost per installed kilowatt. Some of the cost reduction was due to the effect of learning on the part of engineers who were able to build the plants more efficiently (the learning curve). However, the increase in plant capacity — the economy of scale — was the most significant factor in reducing costs.

In this section we will examine the empirical evidence of the scale law in process equipment, large electric equipment, power plants, electric utilities, and operations and maintenance of power plants.

3.1 PROCESS EQUIPMENT

Phung et al.[2] have published examples of process equipment cost and the scale exponent $\underline{n}$ (Table 3.1). These examples include furnaces, direct-fired boilers, shell-and-tube heat exchangers, air coolers, pressure vessels, centrifugal pumps and drivers, and process gas compressors. The data were assembled from various engineering data sources and were based on 1968-1969 dollars.

We note from this table that the scale exponent $\underline{n}$ changes between 0.52 for centrifugal pumps and drivers to 0.85 for process furnace and direct-fired boilers. This supports the observation in the previous section that the scale exponent is valid only within a certain range and that it changes from equipment to equipment, system to system, circumstance to circumstance. Application of economy of scale without the appropriate empirical evidence is therefore not valid.

3.2 LARGE ELECTRIC EQUIPMENT AND TECHNOLOGIES

Lee[3] has studied cost versus rating for several pieces of electric equipment with which he was involved in developing and in pricing. These include steam turbine generators, power transformers, high voltage direct current conversion equipment, and transmission lines.

Figures 3.1 through 3.4 show Lee's data. All pieces of equipment exhibit economy of scale within their technological ranges. The rationale for this economy of scale is easy to understand. If the larger equipment is not cheaper per unit rating, then it would not be developed or would not compete well in the marketplace. Larger equipment, as a rule, is developed after the smaller ones, and hence benefits from improvements in technology and logistics. The distinction between economy of scale and learning is not clear in this instance.

Table 3.2 is a determination of n based on Lee's data and assuming equation 4. The economy of scale is frequently steeper at the lower ranges of the rating than at the higher ranges, indicating a trend towards diminishing return. This trend is also simple to understand. When the technology is extended, one encounters limitations in the strength of materials, fabrication facilities, transportation facilities, and market demand.

A range of relative costs for transmission lines was given by Lee due to the dependence of transmission line costs on tower design and on terrain. Note also that the relationship between MW-mile and kV-mile is quadratic.

3.3 FOSSIL-FIRED AND NUCLEAR POWER PLANTS

Bowers et al.[4] made a literature survey to determine how the cost-size relationship in electric generating stations was viewed by planners, economists, and engineers. They found 34 sources published or reported between 1965 and 1982.

Only seven of these 34 sources deal with empirical data; the others deal mostly with engineering estimates or the proffering of learned judgment. In addition, an empirical work by the General Electric Company (GE) was not reviewed by Bowers et al. The results of these eight empirical studies are tabulated in Table 3.3.

The GE Study

The results of the GE study were reported by Lee[3]. This study compiled cost data for 305 fossil-fired power plants built in the United States between 1960 and 1972, using the cost information reported by the utilities to the Federal Power Commission (Figure 3.5). The economic conditions during the 1960-1972 period were relatively stable and the construction time was not too long; therefore, inflation did not distort the cost figures as much as it did during the 1970s. The GE analysis attempted to establish a causal relationship between the plant costs and factors such as plant rating, multiple units, outdoor or indoor turbine, and public or private owners.

The first cut of the study attempted to normalize the data by comparing the average cost (in $/kWe) of all units completed in the same year and then using that as a base to get ratios of the individual units. Next, the Gross National Product (GNP) deflator was applied to take the time element out of the average costs. Finally, the data so normalized were analyzed for the effect of specific causal factors. For example, all units with outdoor boilers were isolated and their average cost in $/kWe was calculated. The ratio of this average capital cost to the average of all 305 units became an index of how significant that causal factor might be. An index with +2.5 percent impact was judged significant. Table 3.4 lists the results of the significant factors.

Figures 3.6 through 3.8 show the impact of plant size on cost for four cases:

(a) normalized cost of all 305 fossil-fueled power plants
(b) normalized cost of supercritical units
(c) normalized cost of all units adjusted for GNP deflators
(d) normalized cost of all units adjusted for GNP deflators with a two-year lag

Several observations can be discerned:

(a) There is a definite trend towards lower cost as the plant size increases.
(b) There is also learning as utilities build more than one unit on the same site.
(c) As the plant size increased above 200 MWe in the 1960s, the trend was towards supercritical steam conditions (3400 psia, $1000^{o}F$). While these supercritical boilers also showed some economy of scale ($n = 0.72$), there was a cost penalty to use supercritical boilers between 200 and 400 MWe.
(d) The scale exponent between 300 MWe and 900 MWe is approximately between 0.22 and 0.28 both for the GNP adjusted case and for the case with two-year lag in GNP adjustment.

Mooz Studies, 1978 and 1979

Mooz[5] of the Rand Corporation collected data for 39 completed nuclear plants. The regression equation contains a linear term ($n = 1$) for the size factor. When the overall regression results were plotted against reactor sizes, however, he found $n = 0.8$ for the range of 500-800 MWe, $n = 0.5$ for the range of 1100-1200 MWe, and $n = 0.7$ for the range of 500-1200 MWe.

A follow-up analysis by Mooz[6] in 1979 included data for 55 nuclear units. With the expanded data base, he found that costs appear to increase linearly ($n = 1$) with the size of the plant with no saving in unit cost as the size increases.

Stewart Study, 1979

Stewart[7] made an econometric analysis of the average cost of power generation related to factors such as unit size, heat rate, location, and the number of units per site. No distinction between coal, oil, and gas was made. He found little effect of size on the unit cost of equipment ($/kW). Although in an alternate specification of the regression equation, the cost in $/kWe declined as the size increased, he concluded that little faith can be put on the sign of the elasticity of steam plant cost with respect to unit size.

Nieves Study, 1980

Nieves et al.[8] made a regression analysis of historical power plant construction costs as a function of unit size, year of initial commercial operation, and regional location in the United States for both coal-fired and nuclear generating units. The regression equations include dummy variables indicating whether or not the plant is located in the South and indicating whether a flue gas desulfurization system was installed when the plant was built. The regression equation for nuclear plants includes dummy variables for turnkey construction, cooling towers, and plant location. The costs were adjusted to constant dollars using information from the Handy-Whitman Index of public utility construction costs. The regression equation given by Nieves et al. was used by Bowers et al.[4] to determine the costs for different size units and to deduce the cost-size scale exponent. The results were n = 0.52 for coal-fired units and n = 0.25 for nuclear units.

Komanoff Study, 1981

Komanoff[9] hypothesized that power plant capital costs in the 1970s depended on the cumulative capacity of the technology (coal or nuclear) in addition to other factors such as location, architect-engineer, vendor, and size. He collected historical data from utilities as these data were reported to the Federal government, then adjusted the data to a constant dollars basis by using the Handy-Whitman index and by eliminating the interest during construction.

Table 3.5 shows Komanoff's regression equation for 116 coal-fired units completed between 1972 and 1977, totaling 70,509 MWe. Table 3.6 shows his regression equation for 46 nuclear units completed between 1971 and 1978, totaling 39,265 MWe.

Komanoff found no economy of scale for coal-fired units and n = 0.8 for nuclear units. The positive correlation between cost and cumulative capacity indicates that there was a trend for capital cost to increase as more and more units were built (or as time elapsed). This was certainly the reality in the 1970s due to increases in regulation requirements affecting the scope of design and construction. However, Komanoff did not include retrofit costs of earlier plants; hence, his regression analysis has only limited validity. In addition, there is no technical or engineering reason why the cost of a plant should increase as more plants are built unless one has evidence that society is basically against a technology as it grows beyond a certain critical size.

Construction Labor Demand System, Department of Labor, 1982

The Construction Labor Demand System[10] of the Department of Labor made a regression analysis of data compiled in a 1981 special survey of utilities. The objective of the study was to provide a consistent set of estimates for capital costs and construction labor requirements. The reported capital costs were converted to 1980 dollars by utilizing the Handy-Whitman index. With respect to the cost-size relationship, the report found n = 0.92 for coal-fired plants and n = 0.63 for nuclear plants.

National Economic Research Associates, Inc., 1982

Perl[11] of the National Economic Research Associates, Inc., performed regression analyses of historical costs of 33 nuclear units and 245 coal-fired units. The cost-size relationship was determined to be n = 0.7976 for coal-fired units and n = 0.4937 for nuclear units.

3.4 ELECTRIC UTILITIES

Several economists have used statistical and econometric techniques to study economy of scale in the electric utility industries.

Ling[12] made an exhaustive analytical analysis of economy of scale for several electric utilities in the late 1950s. He found that both investment and operating cost are decreasing functions of system capacity. He found the following scale exponents for the total cost of generation at four utilities:

	Range of validity	Utility size scale exponent n
Consolidated Edison	1000 - 4000 MWe	0.493
Detroit Edison	1000 - 4000 MWe	0.668
Philadelphia Electric	1000 - 4000 MWe	0.544
Commonwealth Edison	1000 - 4000 MWe	0.652

Across company lines, the cost of generation also depends on the size of the generating unit. The scale exponents for coal-fired power plants were found to be as follows:

	n
Capital cost	0.854
Fuel cost	0.896
Labor cost	0.487

Dhrymes and Kurz[13] examined the impact of technological progress and economy of scale in the electric utility industry for the period 1937-1959. They found that the economy of scale was valid and the impact of technology was particularly strong during the 1950s.

Christensen and Greene[14] held that economy of scale is steepest at the small-size end, becomes level for a wide range, and then reverses at the very large sizes. They found that there were significant scale economies for nearly all firms in 1955. By 1970, the bulk of U.S.

electricity generation was by firms operating at their maximum economy of scale (flat area of the curve). They concluded that a small number of extremely large firms may exhibit diseconomy of scale. Researches by Huettner and Landon[15] and Seitz[16] indicated similar findings. Figure 3.9 illustrates the diseconomy of scale for large electric utilities as found by Christensen and Greene.

Stigler[17] recognized in 1958 that there is a fairly wide range of optimum sizes -- the long run marginal and average cost curves of the firm are customarily horizontal over a long range of size. Since a number of factors may be relevant in determining the optimum plant size, decision makers must be alert in identifying these factors if they are to make correct decisions.

3.5 FUELS AND OPERATIONS AND MAINTENANCE COSTS

The power generation cost consists of capital, fuel, and operations and maintenance costs typically in the ratio 0.6/0.2/0.2 for nuclear plants and 0.4/0.45/0.15 for coal-fired plants. Economy of scale also extends to some fuel and O & M cost components.

The economy of scale for fuel is relatively small ($n \approx 1$) for coal but could be large ($n < 1$) for nuclear fuel. This is because the nuclear fuel cycle cost involves components such as transportation and expert services which do not depend on whether the reactor is large or small. At this time we have not been able to compile empirical data on the economy of scale of the fuel components for either coal-fired or nuclear power plants.

Myers et al.[18] have been following the O & M costs for both coal-fired and nuclear plants for a number of years. They found little or no dependence of the number of plant personnel on the size of the generating units between 800 and 1200 MWe. Factors other than size are much more important to the O & M costs. For nuclear plants, these include increases in regulatory requirements and quality assurance since the Three Mile Island accident. For coal-fired plants, the flue gas scrubbing operation and the age of the plants affect staffing requirements.

Tables 3.7 and 3.8 illustrate the O & M costs for a nuclear and coal-fired plants, respectively, for the period before and after the TMI accident. Tables 3.9 and 3.10 illustrate the site staff requirements as of 1982.

Figure 3.10 shows the results of the OMCOST computer cost for the O & M cost per kWh as a function of unit rating and multiple units at a coal-fired power plant. The curve for the single-unit plant shows an economy of scale exponent $n = 0.1$ in the range 400-1000 MWe. The curve for the double-unit plant shows an economy of scale exponent of 0.45 between 800 and 2600 MWe.

4. USE OF ECONOMY OF SCALE

The economy-of-scale law was used extensively during the 1960s and 1970s as power plants were built at ever larger sizes. In particular, the design of nuclear plant evolved very rapidly during this period, from about 200 MWe size in 1958 to 1300 MWe size in 1970. Also, during the 1970s several renewable energy technologies, such as solar cells and biomass, were promoted. Their products were not cost competitive with fossil and nuclear energy but were believed to be competitive if the scale of production were expanded.

The use of the economy of scale in the economic analysis of several energy technologies during the 1970s is outlined below.

4.1 ENERGY ECONOMIC DATA BASE AND IN THE CONCEPT CODE

Since the early 1970s, United Engineers and Constructors, Inc., (UE & C) has been doing cost estimates for hypothetical power plants of various fuel types: uranium, coal, oil, and natural gas. The work has been supported by the Department of Energy and the Nuclear Regulatory Commission and their predecessors. A series of reports[19-24] has been published, the latest of which is DOE/NE-0052 (July 1983). Data in these reports constitute a major basis for the CONCEPT code which is compiled and maintained by Oak Ridge National Laboratory[25].

The approach used by UE & C includes defining the design basis, fixing certain standards and regulations, using current material and price data (as of the date of estimate), and estimating the "overnight" cost of a power plant. While the track record of these cost estimates has been poor because of the moving targets in the turbulent 1970s, the same systematic approach was applied for all plant types and for all plant sizes.

Table 4.1 shows the cost-size scaling exponents used in the CONCEPT code. Note that each component of the plant has different scaling exponents.

Table 4.2 shows the evolution of cost-size exponents used by UE & C and by Oak Ridge National Laboratory (ORNL) over a period of 16 years[19-28].

Delene et al.[29] have backed out the size scaling exponents from the CONCEPT code. These exponents have been shown in Table 4.1 and are different for different components. A value of $n = 0.5$ is shown for nuclear plants and $n = 0.62$ for coal-fired plants, suggesting a very steep economy of scale for both.

The values of the scale exponent suggested by Delene et al. are corroborated by the results of the computer outputs of CONCEPT[28], shown in Tables 4.3 and 4.4. The results are shown in 1984 dollars for three sizes of nuclear and coal-fired plants hypothesized to be ordered for a location near Atlanta, Georgia. The sizes of the units are 400 MWe, 800 MWe, and 1200 MWe. The costs shown include direct, indirect, and contingency components. The direct costs were further broken into seven major plant accounts and for each account into equipment, material, and labor.

Figures 4.1 and 4.2 are reproduced from the Reference Book For The Energy Economic Data Base Program (EEDB), DOE/NE-0052.[24] In these figures, UE & C alluded in their "results" that a scaling factor of n = 0.7 is applicable to LWRs and a scaling factor of n = 0.45 is applicable to prospective reactors such as the liquid metal fast breeder and the Consolidated Nuclear Steam Supply (CNSS) reactor. It also reported a scaling exponent of n = 0.24 for the German experience. However, these values were not supported by written documentation or by the quality of the data points.

4.2 AGENCIES, VENDORS, AND ARCHITECT ENGINEERS

Table 4.5 tabulates the use of the economy of scale by members of the various organizations in their cost estimates for coal-fired and nuclear units. These organizations include the Electric Power Research Institute, the International Atomic Energy Agency, the Department of Energy, Westinghouse, General Electric, Ebasco, Gilbert Commonwealth, and two German organizations[30-43].

Several observations can be made from this table:

1. Economy of scale is more pronounced for nuclear plants than for coal-fired plants.
2. Economy of scale is more pronounced in the lower rating range (100-400 MWe) than in the higher rating range (400-1300 MWe).
3. All organizations believed that economy of scale disfavored small reactors in the 1970s.

This prospective view by engineers is, of course, quite different from the retrospective view by economists, as discussed earlier.

One should note that many values in Table 4.8 are not entirely independent from the data in Table 4.2 of ORNL and UE & C. For example, EPRI, IAEA, DOE, and several commercial organizations[30-46] and the 1983 GE study cite the CONCEPT code as a source of data. Perhaps the only independent data is that coming from Germany. Both Mandel of the Rheinisch-Westfalisches Elektrizitatswerke[42] and Gehring of Kraftwerk Union[43] used a scale exponent for nuclear plants more pronounced than that of the CONCEPT code (n = 0.46 to 0.24 as compared to 0.5). These values are applicable only for the range of 600-1300 MWe. For the lower range, they are presumably even more pronounced.

4.3 ECONOMY OF SCALE OF PLANT COMPONENTS

The direct plant cost is usually broken into seven components. Their weighting as determined from the results of the CONCEPT code shown in Tables 4.3 and 4.4 are listed below.

Components of direct cost	Weight	
	Coal	Nuclear
Land and land rights	<0.01	<0.01
Structures and improvements	0.13	0.26
Reactor/boiler plant equipment	0.47	0.30
Turbine plant equipment	0.23	0.24
Electric plant equipment	0.09	0.11
Miscellaneous plant equipment	0.02	0.04
Main condenser heat rejection system	0.05	0.05
Total	1.00	1.00

Table 4.6 shows the results of the survey made in 1975 by Bowers et al.[4] canvassing the scale exponents used by various organizations in their prospective cost estimates for their power plant projects.

4.4 HTGR AND LMFBR COST ESTIMATES

During the 1970s and early 1980s there has been much effort to develop the high-temperature gas cooled reactor (HTGR) and the liquid metal fast breeder reactor (LMFBR). Pilot power plants were designed and built at relatively small ratings for demonstration purposes and for determining the economics of commercialization. For example, the Fort St. Vrain HTGR was built at 330 MWe (but operated at less than full capacity) and the Clinch River Breeder Reactor (CRBR) was designed (but not built) at 350 MWe. Plans for commercial reactors of the same type frequently used the economy-of-scale law to argue that the technology would be competitive at the larger size.

Table 4.7 summarizes the values of the exponent n inherent in the proponents' studies. They all seem to agree with the LWR data from UE & C and from the CONCEPT computer code discussed earlier. Evidence for their validity is lacking, however.

4.5 OTHER TECHNOLOGIES

There have been many capital cost estimates for advanced energy projects including coal gasification, solar cells, biomass, and ocean thermal power plants. These technologies shared the following features: (1) they were supported by government funds, (2) they were not yet commercialized or even built, and (3) they were small in scale.

Practically every cost study of the above nature used the economy-of-scale hypothesis to argue that a particular technology would generate competitive energy if made large enough. To cite a few:

. A large coal gasification facility on the order of 50,000 bbl/day of oil equivalent would exploit economy of scale and would generate competitive gas.[47]

. A cogeneration retrofit for the Illinois Center (a commercial-residential building development near downtown Chicago) is not economic because it is too small.[48]

. It is almost always more attractive to produce synthetic natural gas and power in large separate complexes due to economy of scale.[49]

. The economy of scale achieved by using a large number of one computer vendor's products has resulted in an impressive savings in time and dollars.[50]

. Economy of scale applies for operating a farm of anaerobic digestion of organic residues for methane production. The cost was reduced from $1,700/yr per acre to $690/yr per acre when the farmed area increased from 10 acres to 50 acres.[51]

. There is economy of scale in recycling, storage, and dumping of liquid industrial wastes.[52]

. Economy of scale favors the largest practical size plant. Technology is the limiting factor.[53]

. The production of ammonia from brava cane can enjoy a significant economy of scale as the plant increases in capacity.[54]

. Economy of scale could be applied to solar and wind energy application in Hawaii.[55]

. Economy of scale must be utilized in the materials recovery from industrial waste.[56]

. A larger central processing plant for drying/dehumidification desiccant will enjoy economy of scale.[57]

. The overall economy of scale in producing industrial gas is significantly more pronounced at the lower plant sizes than at higher ones.[58]

. Economy of scale in petroleum refining, storage, and distribution has many factors including nontechnological ones.[59]

5. CONCLUSIONS

The economy-of-scale law is real but depends on many factors. Artisans and technologists have traditionally built prototypes to verify the workability of an idea. If the prototype does not work, the idea is modified or abandoned; if it does, then bigger and better devices are built based on the prototype, with the following generation learning from the preceding generation. Without economy of scale, society would not have those large and wonderfully efficient machines that exist today.

In the power plant sector, economy of scale worked wonders during the 1950s and 1960s. Plant size increased from little more than 100 MWe to well over 600 MWe with the measurable result of decreasing power cost in real terms. However, when plant sizes increased beyond 1,000 MWe in the turbulent 1970s, the point of diminishing return was somehow crossed and no economy of scale was significantly observed. This observation is most noticeable for nuclear reactors which increased fivefold in size within a decade and which went through many problems of construction, operation, and regulation.

There are several components to the final cost of a power plant, each component having its own economy of scale. When engineers speak of a steep scale exponent, say $n = 0.6$ to 0.4, they mean only for the direct and indirect cost components. Due to the stringent regulatory requirements, inflation, high interest rates, and long construction periods, these components assumed a smaller and smaller percentage of the final cost of a nuclear plant during the 1970s — about 40% as of 1984. The other 60% is time dependent and society related.

The 1970s were a turbulent era when the environmental and safety requirements on power plants were increased even during plant construction, when inflation and interest rates were high, and when the construction durations became longer than the estimated durations by two to three times, particularly for plants close to large population centers. Thus, as much as 60% of the final plant cost did not have any economy of scale, or even a negative economy of scale. The economy of scale of the direct and indirect cost components were overwhelmed by these nonengineering cost components.

In the future as power plants become more standardized and regulation more stabilized, we expect that the nonengineering cost components will decrease and the economy-of-scale law will once again be significant in power plant economics.

6. ACKNOWLEDGMENTS

This technical memorandum is an outgrowth of a working paper dated May 28, 1984, that the author prepared for the Nuclear Power Options Viability Study (NPOVS). The author wishes to acknowledge the support of Messrs. Donald B. Trauger and James D. White, the two project leaders of the NPOVS project. Reviews by Howard I. Bowers and Jerry G. Delene are gratefully acknowledged. Dr. Ruth Johnson assisted the author in the 1986 revision of the working paper. The author is, of course, solely responsible for the content.

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Table 2.1. Increasing Share of Non-Size-Related Costs Results in Leveling of the Economy of Scale

A Numerical Example

Plant component	Case 1		Case 2	
	Fraction of cost	Scale exponent	Fraction of cost	Scale exponent
Land	0.01	0.0	—	0.0
Structures and improvements	0.20	0.5	0.11	0.5
Reactor/boiler plant	0.20	0.6	0.09	0.6
Turbine plant	0.10	0.8	0.05	0.8
Electric plant	0.08	0.4	0.04	0.4
Heat rejection plant	0.02	0.8	0.01	0.8
Miscellaneous	0.05	0.3	0.03	0.3
Engineering	0.10	0.2	0.05	0.2
Construction services	0.08	0.45	0.05	0.45
Owners' costs	0.05	0.5	0.05	0.5
Dependent costs	0.11	1.0	0.52	1.0
Overall	1.0	0.554	1.0	0.760

Case 1: Stable conditions, low inflation, low interest rate, short construction duration (typical of the late 1960s)

Case 2: Turbulent conditions, high inflation, high interest rate, long construction duration (typical of the late 1970s)

Table 3.1. Examples of Equipment Cost and Size Relationship

Equipment	Size and range	Point value	Cost Exponent n
Process Furnace	20-300 MMBtu/hr	$100,000; 30 MMBtu/hr unit, field erected	0.85
Direct Fired Boilers	20-30 MMBtu/hr	$20,000; 50 MMBtu/hr unit, field erected, cylindrical, carbon steel	0.85
Shell and Tube Heat Exchangers	200-5,000 ft^2	$7,000; 700 ft^2 unit, as fabricated, 150 psi	0.65
Air Coolers	200-5,000 ft^2	$20,000; 2,000 ft^2 unit, field erected carbon steel	0.80
Pressure Vessels	2'OD x4'H to 10'OD x 100'H	$10,000 per unit 4.3 ft OD x 40 ft high vertical, carbon steel, 50 psi	0.65 vertical 0.60 horiz.
Centrifugal Pumps and Drivers	4,000-200,000 C/H Factor (gpm x psi)	$2,000 per unit, centrifugal cast iron C/H = 35,000	0.52
Process Gas Compressors	30-10,000 Bhp (Brake horsepower)	$140,000/1,000 Bhp, carbon steel centrifugal	0.82

Sources: Doan L. Phung et al., "Assessment of Industrial Energy Conservation by Unit Processes," Institute for Energy Analysis, Oak Ridge Associated Universities, Report ORAU/IEA-80-4 (R), March 1980.

Note: Some data on equipment costs and cost exponents were taken from:

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Off-the-shelf prices for equipment were also taken from specific manufacturers (e.g., Babcock and Wilcox Handbook on prices of furnaces).

Table 3.2. Economy of Scale for Large Electric Equipment

	Scale exponent n
Fossil Steam Turbine Generators	
350 - 700 MW	0.68
500 - 1000 MW	0.69
Power Transformers	
230 kV	
200 - 400 mva	0.58
400 - 800 mva	0.67
600 - 1200 mva	0.74
345 kV	
200 - 400 mva	0.46
400 - 800 mva	0.67
600 - 1200 mva	0.80
500 kV	
200 - 400 mva	0.47
400 - 800 mva	0.55
600 - 1200 mva	0.75
High Voltage DC Conversion Equipment	
100 - 1000 MW	0.78
1000 - 4000 MW	0.84
Transmission Lines[a]	
225 - 500 kV	0.98; 1.20[b]
500 - 765 kV	0.80; 0.69
765 - 1100 kV	0.59; 0.28

Source: Values were estimated from graphical data by Thomas Lee, "the Case for Evolutionary Optimization," Future Strategies for Energy Development - Question of Scale, proceeding of a conference ORAU-130, Oak Ridge Associated Universities, P. O. Box 117, Oak Ridge, TN, pp. 229-256 (1976).

[a] Note that the relationship between MW-mile and kV-mile is quadratic.

[b] Values were estimated for each of the two curves given by Lee.

Table 3.3. Empirical Evidence of Cost-Size Relationship in Power Plants

Study	Cost exponent n Coal	Cost exponent n Nuclear	$/kWe exponent s Coal	$/kWe exponent s Nuclear
1. Lee, 1976	0.85	na	-0.15	na
2. Mooz, 1978	na	0.5-0.8	na	-0.5 to -0.2
3. Mooz, 1979	na	1	na	0
4. Stewart, 1979	[a]	na	[a]	na
5. Nieves et al, 1980	0.52	0.25	-0.48	-0.75
6. Komanolf, 1981	1.00	0.80	0	-0.20
7. Construction Labor Demand System, 1982	0.92	0.63	-0.08	-0.37
8. Perl, 1982	0.80	0.49	-0.20	-0.51

[a] Stewart concluded that "Although there is some decrease in $/kW with respect to the size of the unit, this is small. Little faith can be put on the sign of the elasticity (scale exponent) of steam plant cost with respect to unit size."

Table 3.4. Index for Parameters Affecting Capital Costs of 305 Fossil Fuel Plants (1960-1972)

	Average MWe	No. of units	$/kWe	Cost index
National	343	305	127.46	1.0
First units	381	80	143.47	1.126
Second units	354	76	122.86	0.964
Nonfirst and nonsecond units	317	149	119.73	0.939
Conventional construction	347	202	128.97	1.012
Outdoor construction	334	103	124.39	0.976
Coal-fired	363	249	126.98	0.996
Dual-fuel	251	56	130.54	1.024
Private utilities	366	258	126.20	0.99
Public utilities	215	47	139.24	1.092
Conventional boilers	258	237	127.87	1.003
Supercritical boilers	640	68	126.88	0.995

Source: Thomas H. Lee, "The Case of Evolutionary Optimization," Future Strategies For Energy Development - A Question of Scale, proceeding of a conference ORAU-130, Oak Ridge Associated Universities, P. O. Box 117, Oak Ridge, TN, pp. 229-256 (1976)

Table 3.5. Komanoff's Regression Equation for 116 Coal-Fired Units Completed Between 1972-1977

$$\$/KWe = 0.234\ f_1\ f_2\ f_3\ f_4\ f_5^{0.615}$$

where

f_1 = Location factor; 1.14 if Northeast, 1.26 if West, 0.76 if South Central, 0.86 if Southeast (excluding Southern Company)

f_2 = Company factor; 0.73 if Southern Company, 1.18 if American Electric Power

f_3 = Multiple unit factor; 1 if single unit, 0.904 if multiple unit

f_4 = Scrubber factor; 1.26 if having scrubber

f_5 = Cumulative nationwide coal installed capacity factor; this was 260,400 MWe in 1971

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

Table 3.6. Komanoff's Regression Equation for
46 Nuclear Units Completed Between 1971 and 1978

$$\$/KWe = 6.41\ f_1\ f_2^{-0.105}\ f_3\ f_4\ f_5\ MW^{-0.2}\ f_6^{0.577}$$

where

f_1	=	1.28 if location is Northeast, 1 elsewhere
f_2	=	The number (1 or more) of reactor the architect-engineer has been involved in
f_3	=	0.903 if multiple unit, 1 if single unit
f_4	=	1.34 if "dangling," that is, if the unit was still under construction at the time of analysis but some cost numbers had already been available
f_5	=	1.20 if the unit has cooling towers, 1 if once-through cooling
MW	=	Unit size
f_6	=	Cumulative nuclear capacity in the nation

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

Table 3.7. Comparison of 1982 and 1978 Annual O&M Cost-Estimating Guidelines for a 1 x 1150 MWe PWR Plant at 65% Capacity Factor (millions of 1982 dollars)

	1978	1982
Onsite staff	6.6	14.8
Maintenance materials	2.3	4.3
Supplies and expenses	6.0	5.5
Regulatory fees, inspections, and reviews	0.1	0.5
Offsite support services	0	3.7
Insurance	0.4	6.0
Administrative and general	2.2	8.6
Total	17.6	43.4

<u>Source</u>: M. L. Myers, L. C. Fuller, and H. I. Bowers, "Nonfuel Operation and Maintenance Costs for Large Steam-Electric Power Plants - 1982," ORNL/TM-8324, Oak Ridge National Laboratory, Oak Ridge, TN (September 1982).

Table 3.8. Comparison of 1982 and 1987 Annual O&M Cost-Estimating Guidelines for a 2 x 575 MWe Coal-Fired Plant at 65% Capacity Factor (millions of 1982 dollars)

	1978	1982
Onsite staff	9.9	9.5
Maintenance materials	4.2	4.0
Supplies and expenses	16.7	13.5
Regulatory fees, inspections, and reviews	0	0
Offsite support services	0	1.1
Insurance	0	0.2
Administrative and general	1.7	8.4
Total	32.5	36.7

Source: M. L. Myers, L. C. Fuller, and H. I. Bowers, "Nonfuel Operation and Maintenance Costs for Large Steam-Electric Power Plants - 1982," ORNL/TM-8324, Oak Ridge National Laboratory Oak Ridge, TN (September 1982).

Table 3.9. Onsite Staff Requirement for LWR Power Plants (800–1200 MWe Unit Size)

Function	Units per site 1	2	3	4
Plant manager's office				
Manager	1	1	1	1
Assistant	1	2	3	4
Quality assurance	6	6	7	8
Environmental control	1	1	1	1
Public relations	1	1	1	1
Training	12	12	12	12
Safety and fire protection	1	2	3	4
Administrative services	49	55	65	78
Health services	2	2	2	2
Security	94	94	94	94
Subtotal	168	176	189	205
Operations				
Supervision (excluding shift)	9	9	18	18
Shifts	52	104	156	208
Subtotal	61	113	174	226
Maintenance				
Supervision	12	14	26	28
Crafts	55	71	87	103
Peak maintenance annualized	55	110	165	220
Subtotal	122	195	278	351
Technical and engineering				
Reactor	5	5	7	7
Radiochemical	8	8	12	12
Engineering	16	16	16	16
Performance, reports, and technicians	21	30	39	48
Subtotal	50	59	74	83
Total	401	543	715	865
If not including security	307	449	621	771
If not including security and peak maintenance	252	339	456	551

Source: M. L. Myers, L. C. Fuller, and H. I. Bowers, "Nonfuel Operation and Maintenance Costs for Large Steam-Electric Power Plants - 1982," ORNL/TM-8324, Oak Ridge National Laboratory Oak Ridge, TN (September 1982).

Table 3.10. Onsite Staff Requirement for Coal-Fired Power Plants Without FGD Systems (400-800 MWe Unit Size)

Function	1	2	3	4
		Units per site		
Plant manager's office				
Manager	1	1	1	1
Assistant	1	2	3	4
Environmental	1	1	1	1
Public relations	1	1	1	1
Training	1	1	1	1
Safety	1	1	1	1
Administrative services	12	13	14	15
Health services	1	1	1	2
Security	7	7	7	7
Subtotal	26	28	30	33
Operations				
Supervision (excluding shift)	2	2	4	4
Shifts	45	50	60	65
Fuel handling	12	12	12	18
Subtotal	59	64	76	87
Maintenance				
Supervision	6	6	8	10
Crafts	75	90	105	120
Peak maintenance annualized	15	30	45	60
Subtotal	96	126	158	190
Technical and engineering				
Chemical	2	2	3	4
Instrumentation and controls	2	2	3	4
Technical performance and reporting	12	15	18	21
Subtotal	16	19	24	29
Total	197	237	288	339

Source: M. L. Myers, L. C. Fuller, and H. I. Bowers, "Nonfuel Operation and Maintenance Costs for Large Steam-Electric Power Plants - 1982," ORNL/TM-8324, Oak Ridge National Laboratory Oak Ridge, TN (September 1982).

Table 4.1. Cost-Size Scaling Exponents
Used in the CONCEPT Code

Account	Scaling exponents Nuclear	Coal
Direct costs		
Land and land rights	0.0	0.0
Structures and improvements	0.50	0.55
Reactor/boiler plant equipment	0.60	0.60
Turbine plant equipment	0.80	0.75
Electric plant equipment	0.40	0.50
Miscellaneous plant equipment	0.30	0.25
Main condenser heat rejection system	0.80	0.95
Indirect costs		
Construction services	0.45	0.60
Home office engineering and services	0.20	0.60
Field office engineering and services	0.40	0.70
Owner's costs	0.50	0.60
Cost-weighted average	0.50	0.62

Source: Jerry Delene et al., A Reference Data Base for Nuclear and Coal-Fired Power Generating Cost Analysis, Oak Ridge National Laboratory, Oak Ridge, TN (February 1984).

Table 4.2. Chronological Use of Economy-of-Scale Exponents by United Engineers and Constructors, Inc., and by Oak Ridge National Laboratory

Organization	Cost exponent n: Coal-fired	Cost exponent n: Nuclear
UE & C		
1966	0.76	na
1968	na	0.75
1978	0.70	0.45
1979	0.74	na
1981	0.70	0.40
1982	na	0.63
1983	na	0.70 LWR
		0.45 CNSS
		0.24 German
ORNL		
1971	0.77	0.68
1982	0.62	0.50

Source: Data assembled from H. . Bowers et al., Trends in Nuclear Power Plant Capital Investment Cost Estimates - 1976 to 1982, NUREG/CR-3500, ORNL/TM-8898, Oak Ridge National Laboratory, Oak Ridge, TN (September 1983).

Table 4.3. PWR Cost Structure In ORNL CONCEPT Code (3/84)
(millions of 1984 dollars)

	400 MWe	800 MWe	1,200 MWe
Land and land rights	5	5	5
Structures	176	249	305
Reactor plant	179	272	347
Turbine plant	114	199	275
Electric plant	85	113	133
Miscellaneous plant	31	38	42
Heat rejection system	22	39	53
Direct, $M	612	915	1,160
Construction services	92	126	151
Home office eng. services	248	285	309
Field office eng. services	98	130	153
Owner's cost	103	145	178
Indirect, $M	541	686	791
Contingency, $M	172	239	292
Total			
$ M	1,325	1,840	2,243
$/kW	3,313	2,300	1,869

Source: H. Bowers, run of the CONCEPT Code for Doan L. Phung for coal-fired plants and PWR plants at 400, 800, and 1200 MWe (March 30, 1984).

Table 4.4. Coal-Fired Plants Cost Structure
In ORNL CONCEPT Code (3/84)
(millions of 1984 dollars)

	400 MWe	800 MWe	1,200 MWe
Land and land rights	5	5	5
Structures	57	84	106
Boiler plant	194	295	377
Turbine plant	82	139	189
Electric plant	41	58	71
Miscellaneous plant	15	18	20
Heat rejection system	15	28	41
Direct, $M	409	627	809
Construction Services	36	55	71
Home Office Eng. Services	24	35	45
Field Office Eng. Services	19	31	42
Owner's Cost	49	75	97
Indirect, $M	128	196	255
Contingency, $M	80	123	159
Total			
$ M	617	946	1,223
$/kW	1,543	1,183	1,019

Source: H. Bowers, run of the CONCEPT Code for Doan L. Phung for coal-fired plants and PWR plants at 400, 800, and 1200 MWe (March 30, 1984).

Table 4.5. Use of Economy of Scale By Various Organizations

Organization	Scale exponent n Coal-fired	Nuclear	Range of validity (MWe) Coal-fired	Nuclear	Remarks (D=direct cost I=indirect T=total cost)
EPRI, 1982	0.85	0.53	500-1000	500-1200	D&I, Ref. 30
IAEA, 1976	na	0.71	na	600-1200	D&I, Ref. 31
1979	0.75	0.40	300-800	600-1200	D&I, Ref. 32
	0.65	0.49	600-1000	600-1000	T
DOE, 1979	0.76	na	900-1300	na	D&I, Ref. 33
W, 1977	0.81	0.86	na	na	T , Ref. 34 Empirical example
GE, 1969	0.64	0.75	500-1100	500-1100	T , Ref. 35
1975		0.47		660-1220	T , Ref. 36
1983	0.85	0.25	500-1000	600-1200	T , Ref. 37
EBASCO, 1976	na	0.73	na	400-1260	T , Ref. 38
1981	0.68	na	200-800	na	T , Ref. 39 2-unit Subcrit.
	0.76	na	600-1200	na	T , 2-unit Supercrit.
GILBERT, 1980	0.70	0.43	100-1200	600-1200	D&I, Ref. 40
1981	0.73	0.43	100-600	600-1200	T , Ref. 41
	0.85	na	600-1200	na	T
GERMAN, 1976	0.74	0.46	150-600	600-1300	T , Ref. 42
1979	na	0.24	na	700-1300	D&I, Ref. 43

na = not available

Source: H. I. Bowers et al., Trends in Nuclear Power Plant Capital Investment Cost Estimates - 1976 to 1982, NUREG/CR-3500, ORNL/TM-8898, Oak Ridge National Laboratory, Oak Ridge (September 1983).

Table 4.6. Results of Survey of Cost-Size Scaling

	Structures	Reactor-boiler plant	Turbine plant	Electric plant	Misc. plant
Nuclear Plants					
CONCEPT IV	0.8	0.6	0.8	0.6	0.3
Architect-engineer	0.66	0.66-0.9	0.75	0.45	0.3
Architect-engineer	0.8	0.6	0.8	0.6	0.3
Architect-engineer	0.8	0.6	0.8	0.6	0.3
Architect-engineer	0.8	0.85	0.8	0.8	0.3
Utility	0.95	0.95	0.95	0.95	0.95
Contractor	0.4-0.6	0.6-0.8	0.7-0.9	0.5-0.7	
Manufacturer	0.6	0.6	0.6	0.6	0.6
Fossil-Fired Plants					
CONCEPT IV	0.75	0.9	0.8	0.45	0.3
Architect-engineer	0.66	0.93	0.73	0.45	0.32
Architect-engineer	0.75	0.9	0.8	0.45	0.3
Architect-engineer	0.75	0.9	0.8	0.45	0.3
Architect-engineer	0.75	0.9	0.8	0.45	0.3
Utility	0.92	0.92	0.92	0.92	0.92
Utility	0.7	0.9	0.7	0.6	0.6
Contractor	0.4-0.6	0.6-0.8	0.7-0.9	0.5-0.7	

Source: U.S. Department of Energy, CONCEPT: A Computer Code for Conceptual Cost Estimates for SteamElectric Power Plants, ERDA-108, p. 14 (June 1975).

Table 4.7. Economy of Scale Used In Some HTGR and LMFBR Cost Estimates

	Plant cost exponent n
HTGR Cost Estimates, 100-600 MWe	
Nuclear plants	0.55
Coal-fired plants	0.67
Oil-fired plants	0.93
Gas-fired plants	0.93
LMFBR Cost Estimates, 600-1500 MWe	
Reactor plant	0.41
Structures	0.29
Turbine plant	0.58
Electric plant	0.58
Miscellaneous plant	0.58

Sources:

Colin F. MacDonald and David L. Sonn, "A New Small HTGR Power Plant Concept With Inherently Safe Features - An Engineering and Economic Challenge," American Power Conference, April 18-20, 1983 Illinois Institute of Technology, Chicago, IL (1984).

U.S. Department of Energy, Assistant Secretary of Nuclear Energy, Program Reference Book for the Energy Economic Data Base Program (EEDB), DOE/NE-0052, Appendix B-3, p. 28 (July 1983).

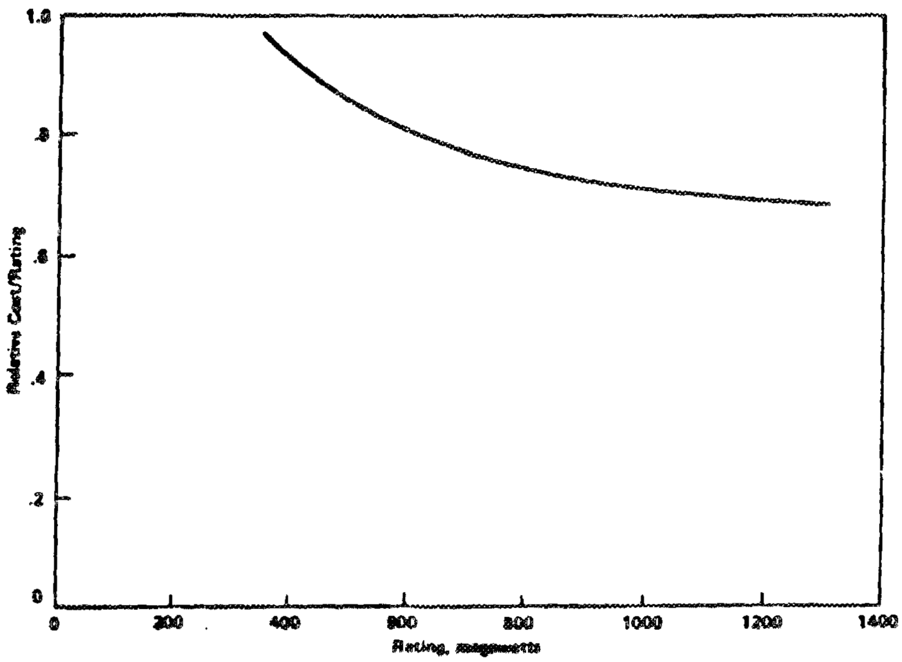

Figure 3.1. Cost and Rating of Fossil-Fired Steam Turbine Generators
<u>Source</u>: Thomas H. Lee, Ref. 3

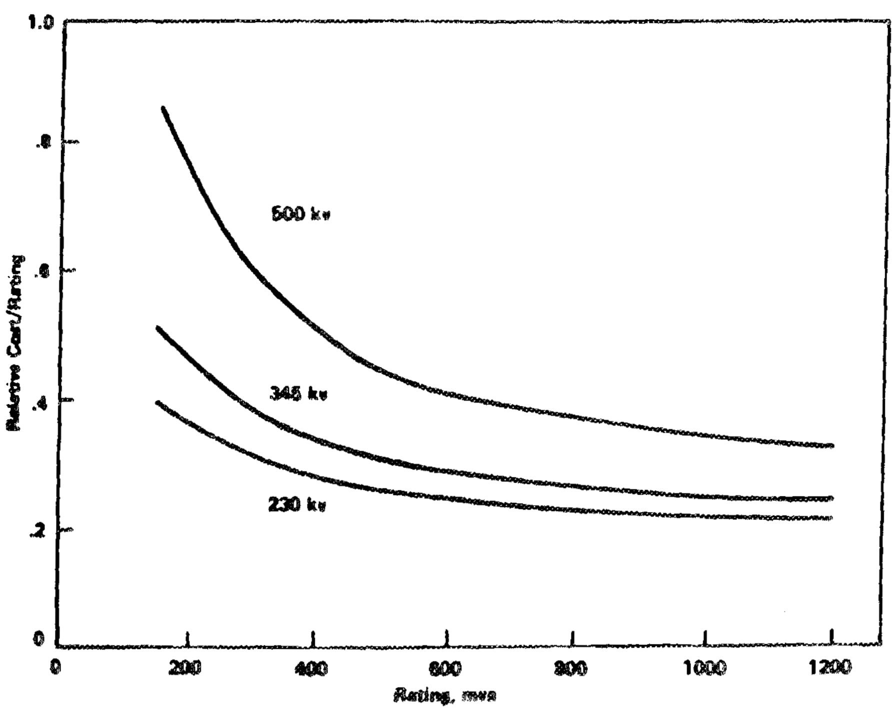

Figure 3.2. Cost vs. Rating of Power Transformers
<u>Source</u>: Thomas H. Lee, Ref. 3

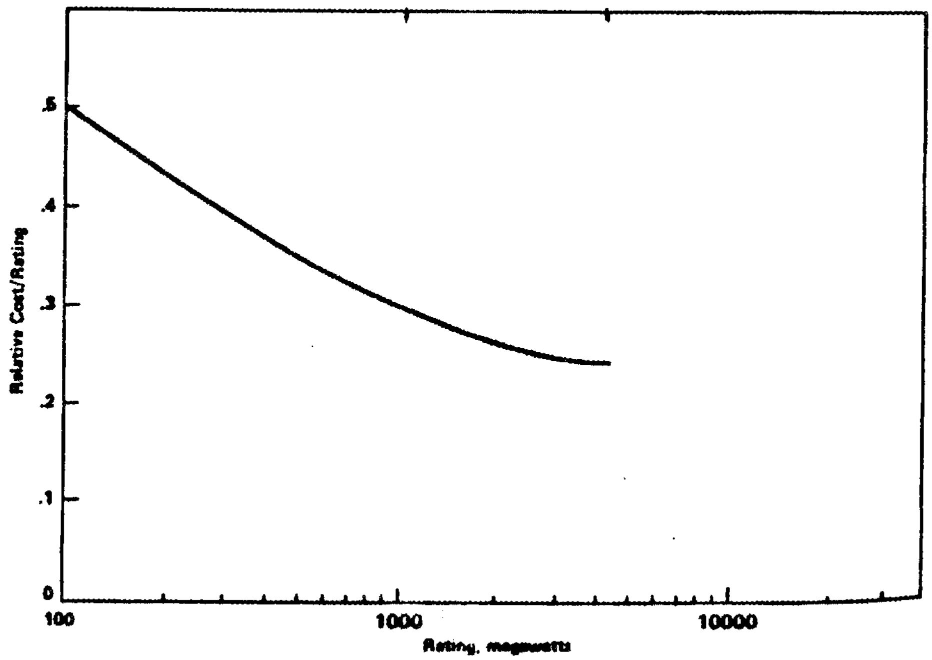

Figure 3.3. Cost vs. Rating of HVDC Conversion Equipment
Source: Thomas H. Lee, Ref. 3

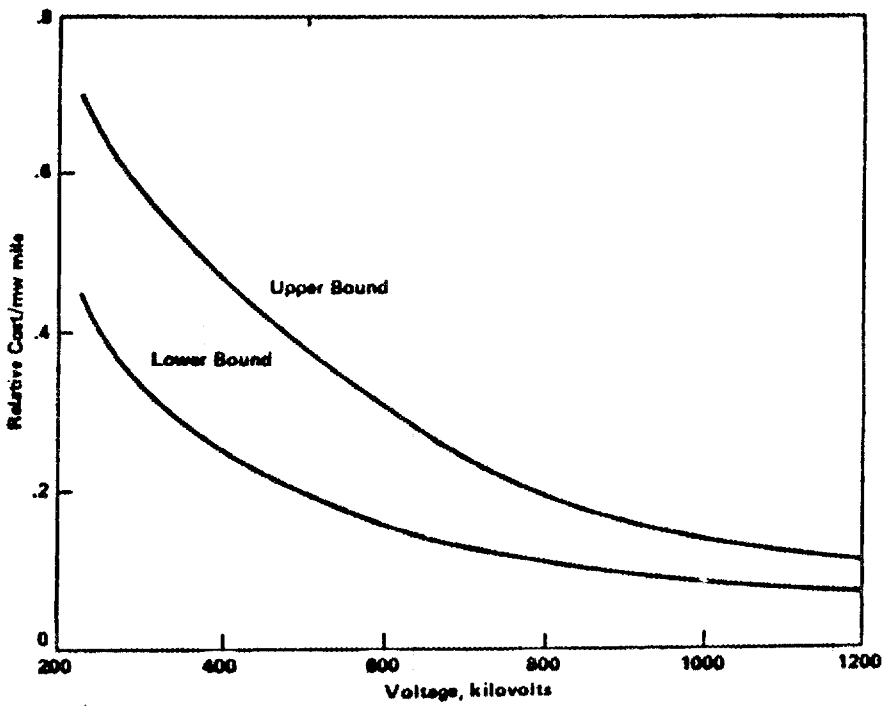

Figure 3.4. Cost vs.Rating of Transmission Lines (Excluding Right-of-Way)
Source: Thomas H. Lee, Ref. 3

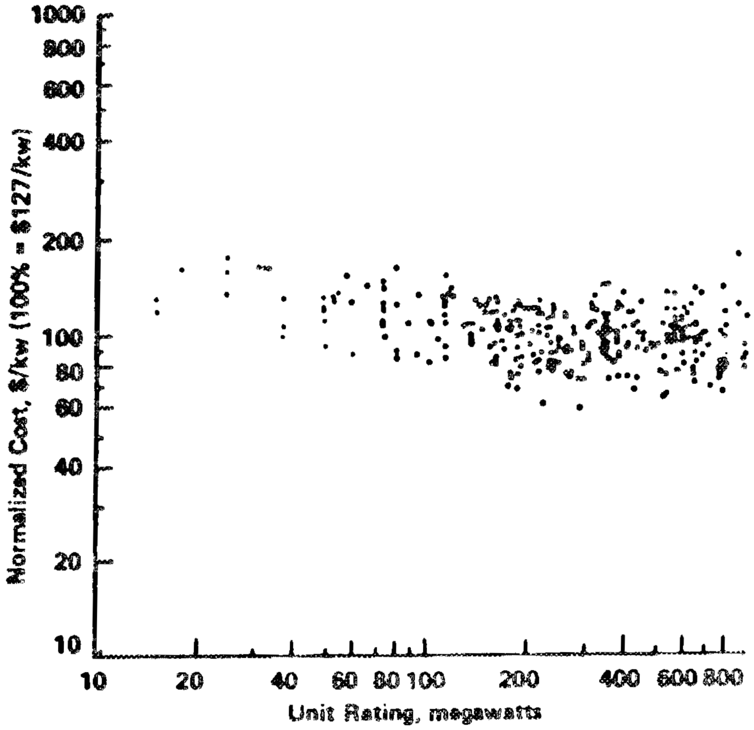

Figure 3.5. Plant Construction Cost of 305 Fossil Fuel Plants vs. Size
<u>Source</u>: Thomas H. Lee, Ref. 3

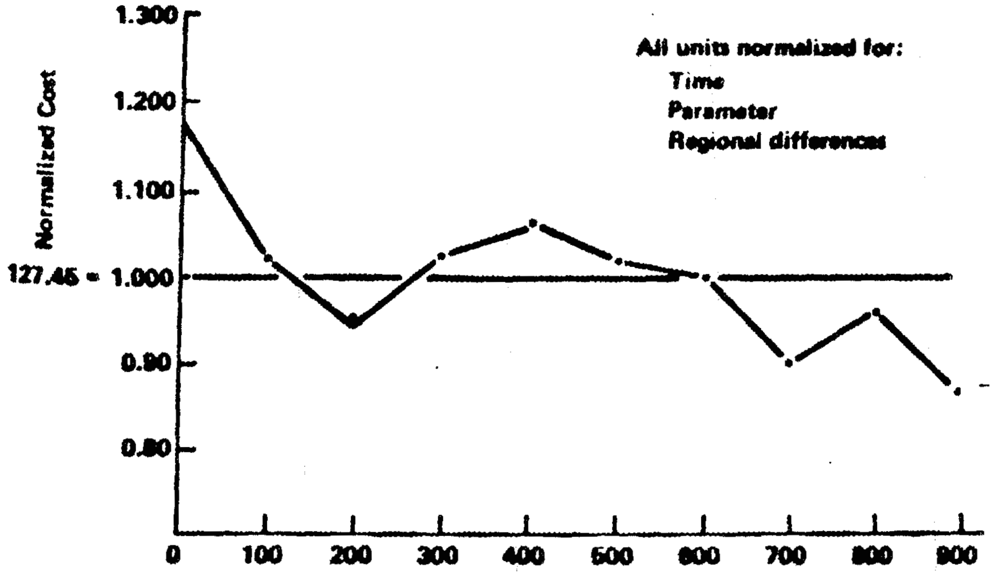

Figure 3.6. Normalized Cost of 305 Fossil Fuel Power Plants vs. Size
Source: Thomas H. Lee, Ref. 3

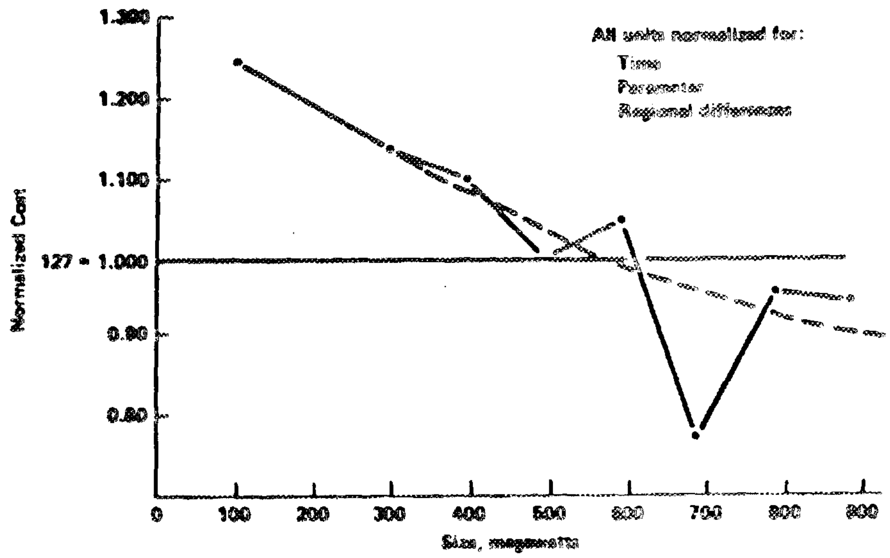

Figure 3.7. Normalized Cost for Supercritical Units of 305 Fossil Fuel Power Plants vs. Size
Source: Thomas H. Lee, Ref. 3

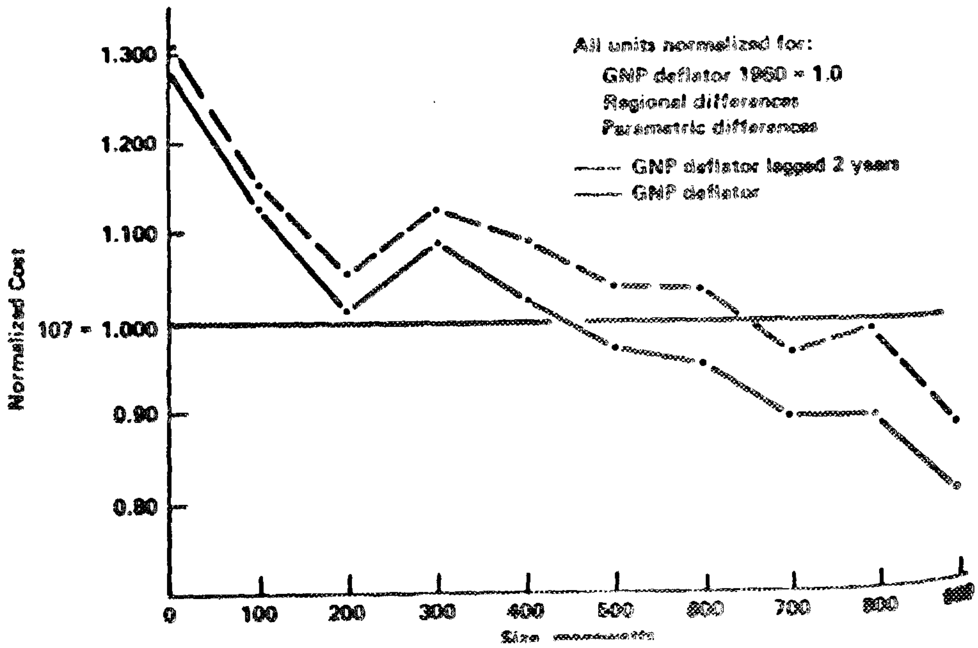

Figure 3.8. Normalized Cost (Including Inflation) of 305 Fossil Fuel Power Plants vs. Size
Source: Thomas H. Lee, Ref. 3

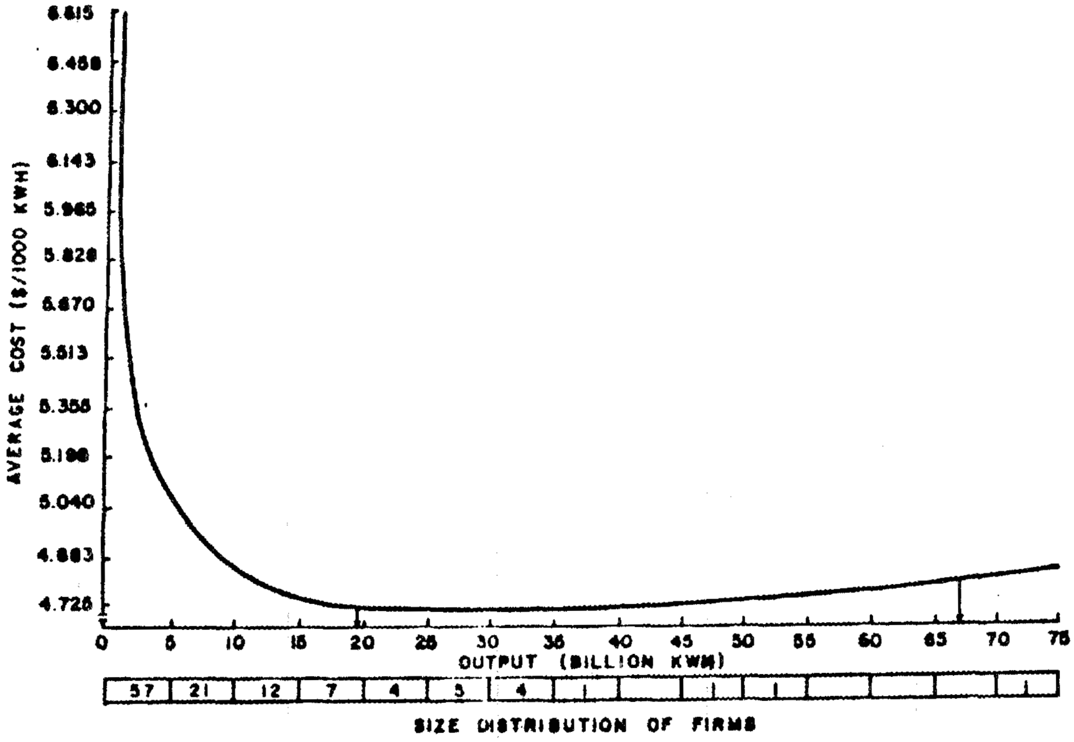

Figure 3.9. Average Cost Curves in $/kWe as Function of Firm Size
<u>Source</u>: L. R. Christensen and W. H. Greene, Ref. 14

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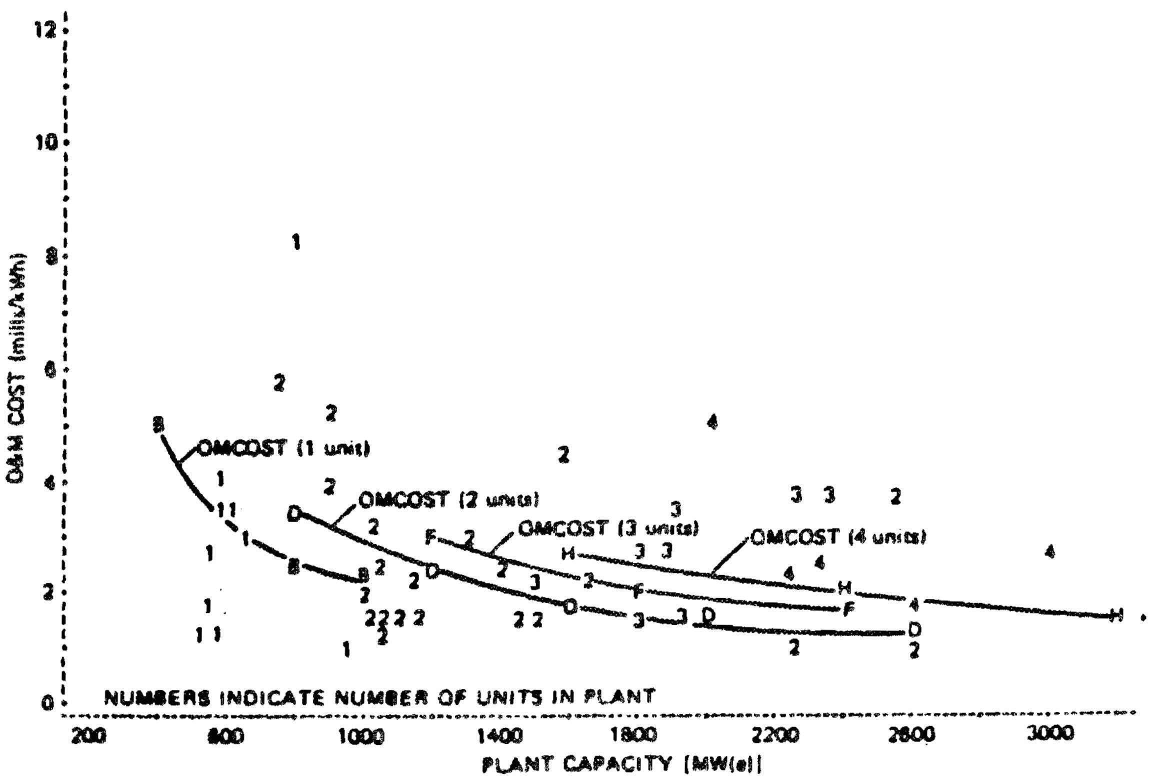

Figure 3.10. Comparison of OMCOST at 60% Capacity Factor With 1980 Reported Costs for Coal-Fired Plants

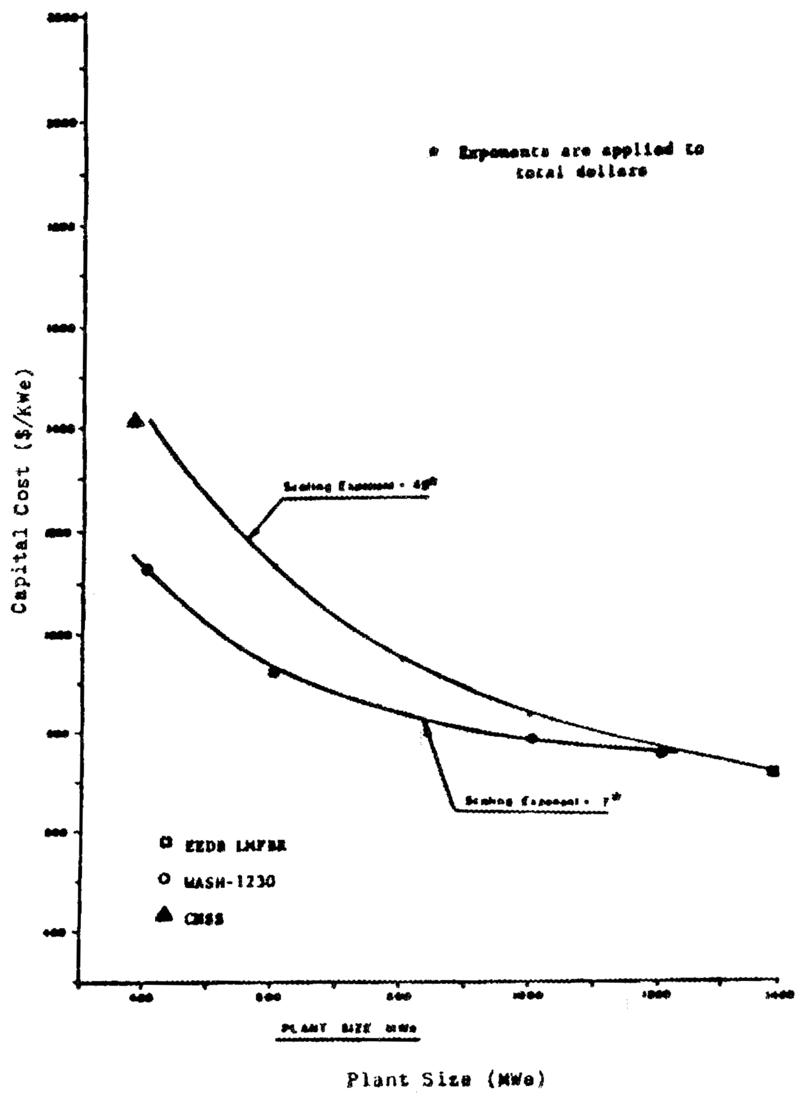

Figure 4-1. Reduction in Incremental Capital Cost With Size — U.S. Experience
Source: U.S. Department of Energy, Ref. 24

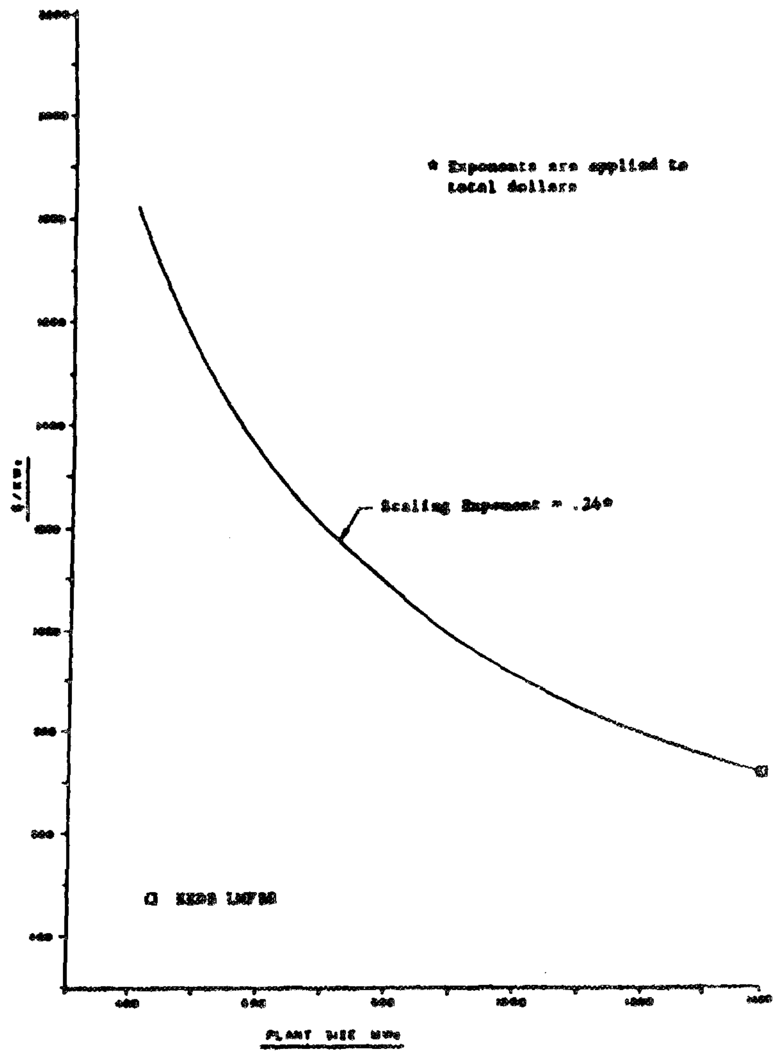

Figure 4.2. Reduction in Incremental Capital Cost With Size — Foreign Experiences
Source: U.S. Department of Energy, Ref. 24

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