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Economics of Nuclear Power

An analysis of when the falling costs of nuclear power will meet the rising costs of conventional power.

John E. Ullmann

It is generally believed that the costs of nuclear power will decrease, and hence it is necessary to attempt a prediction of the time when nuclear power will begin to compete economically with power from conventional steam plants. This is of interest not only to utilities engaged in long-term planning of facilities but also to power users and to equipment manufacturers, who have to assess the competitive pressures exerted by atomic power developments upon their established lines of products. The specific variables of interest are capacity costs and bus-bar costs. Capacity costs are given in dollars per kilowatt of installed generating capacity. Bus-bar costs are the costs of power at the generating station—that is, the costs exclusive of transmission and distribution costs; they are usually given in mills (0.1 cent) per kilowatt hour.

There have been many predictions about the costs of nuclear power. The reasoning behind the growth rate they propose is not, however, generally set forth. The predictions of costs, and hence of break-even points—that is, the time when nuclear and conventional power will cost the same—usually assume that the present conventional power plant capacity and bus-bar costs will remain stable within rather narrow limits. It follows from this view that the price reductions of the future will have to

Mr. Ullmann is on the staff of Columbia University, in the department of industrial and management engineering.

come mainly from the nuclear side and that there will be no corresponding upward movement of conventional costs which would serve to improve the relative economics of nuclear power. This is implied, for example, in the cost charts by Davis and Roddis (*1*) and is specifically listed as an assumption in the McKinney panel report (*2*).

The present analysis is based on two premises. First, it is proposed to review the history of cost reduction in conventional steam plants since 1910 and to apply these rates of cost reduction to nuclear power. In a second step, it is shown that the cost structure of conventional power is likely to prove unstable in the future and that the instability will lead to a considerable rise in costs. The trends from these two analyses are then combined to produce a forecast of break-even points, beyond which nuclear power may be expected to have an increasing economic advantage.

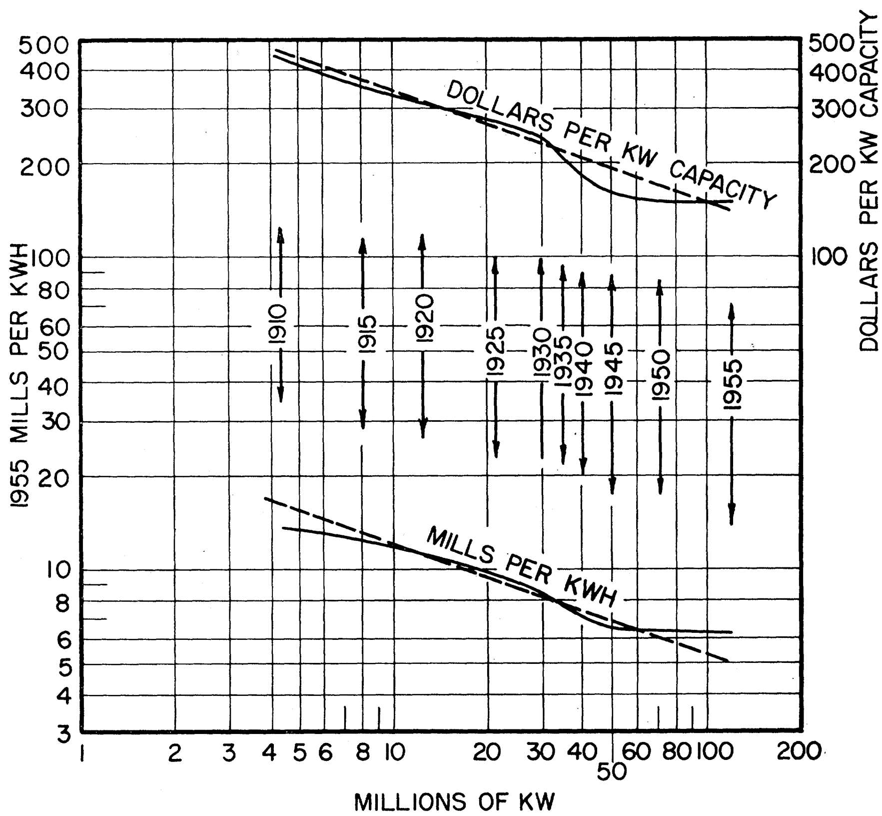

Fig. 1. Cost reductions in conventional steam power, 1910–1955 (*6, 8, 13*).

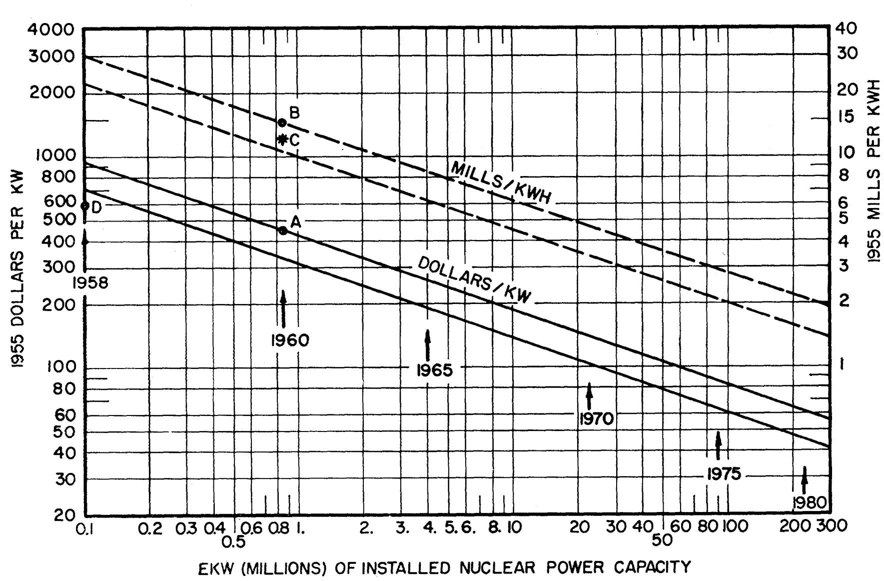

Fig. 2. Anticipated cost reductions in nuclear power, 1958–1980.

Cost Reductions in Conventional Power Plants

The history of the electric power industry in the United States is one of virtually continuous decline in both the investment cost of power plants per unit of capacity and the bus-bar costs of electricity, in the face of increases in the prices of coal and equipment. This trend is shown in Fig. 1, which gives these costs in relation to installed capacity in kilowatts, together with corresponding years. It is thus seen that there is a continuous trend, going back to 1910—some forty-seven years—during which these general reductions have been maintained, even though a recent leveling off is discernible.

It was found that the trend lines fitted to these curves are of almost exactly equal slope (−0.35) and, moreover, that the relationships as a whole bear a resemblance to a "learning curve" (*3*), with "learning" applied to total installed kilowatts rather than to some number of units. With the relationship observed, each successive doubling of capacity has resulted in a 12-percent reduction in cost. The slopes of the curves in Fig. 1, and hence this "learning" rate, are applied to projected costs of nuclear power.

This is considered legitimate because the technologies of the two fields are quite similar, with much equipment—mechanical and, especially, electrical—the same for nuclear as for conventional plants. The equipment is made by essentially the same supplier industry, and the improvements projected for nuclear plants are of the same kind as those with which conventional plants have traditionally neutralized a rising cost level and have actually realized the economies shown in Fig. 1.

For instance, at the Indian Point plant of Consolidated Edison Company of New York, it is proposed to use working pressures of 370 to 420 pounds per square inch (*4*) at a time (1960) when 6000 pounds per square inch or more are envisaged for conventional plants. There is thus quite a margin for refinement in design: working pressures may be increased in nuclear plants, with commensurate economies, just as in conventional plants.

This also implies that problems of safety and waste disposal will be solved. Waste disposal is difficult, though perhaps solutions may be found even before fusion power is developed. The development of fusion power would, of course, reduce the problem greatly. In the absence of adequate operating experience, safety has also dictated very severe standards in the construction of the first plants. Davis and Roddis (*1*) expect this to constitute a major area for potential savings.

In another design area, Fairman (*4*) has noted the substitution of stainless steel for zirconium fuel containers in the reactor core, thus effecting a saving of some 90 percent, even when the forthcoming lower price of zirconium is taken into consideration. This change was predicted a year ago in the report on "Project Size-up" (*5*). Such important changes demonstrate the maneuverability of present nuclear power technology. In future conventional plants, on the other hand, there are likely to be grave design problems in the simultaneous existence of working temperatures approaching those of today's gas turbines and extremely high pressures (4000 to 6000 pounds per square inch compared with about 90 pounds per square inch in a gas turbine). This equipment must further be suitable for prolonged trouble-free operation.

Initial reports on the Shippingport plant indicate that it uses about 25 to 30 percent more operators per shift than a comparable conventional power plant. In a conventional plant, moreover, much of the labor is employed in handling fuel, whereas, in a nuclear plant, much less labor is required for this purpose. Manpower, too, therefore appears to be a likely area for potential savings. Again, Estcourt (*6*) has pointed out that conventional plants cannot expect to reduce their staffs much more. On the basis of these considerations, it may be said that sufficient leeway exists in present nuclear-plant design to warrant the prediction that there will be decreases in present cost estimates similar to the decreases in cost that have occurred in the production of power by conventional means.

Table 1. Estimated capacities and costs for nuclear plants expected to be operating by 1960.

Name	Capacity (kw) (thousands)	Cost estimate (millions of dollars)	Dollars per kilowatt
Duquesne Power & Light Co., Shippingport, Pa.	100	70	700
Power Reactor Development Co. Inc., Monroe, Mich.	100	48	480
Yankee Atomic Electric Co., Rowe, Mass.	134	57	426
Consumer Public Power District, Beatrice, Neb.	75	43	573
Rural Cooperative Power Association, Elk River, Minn.	22	12	546
Commonwealth Edison Co., Dresden, Ill.	180	60	333
Consolidated Edison Co. of N.Y., Indian Point, N.Y.	236	90	381
Totals	847	380	450

Projection of Nuclear Power Costs

In order to project the cost reductions for nuclear power at the rates of cost reductions experienced in conventional plants, it is necessary first to determine the present levels of nuclear power costs. These are then used as the starting points from which progress in cost reduction can be estimated. The reduction rate also depends on the rate of introduction of nuclear plants, just as the decline in cost of conventional power was related to installed capacity. In order to translate the horizontal, or capacity, scale into years, a rate of introduction of nuclear power must therefore be assumed. Here, the rate suggested by Davis and Roddis (*1*) has been used. As these authors point out, their estimate of 67 percent new nuclear capacity relative to total annual new capacity by 1980 is about the same as other estimates, which they cite. However, they are more optimistic than others in estimating the contribution which this will make to total capacity and generation.

With respect to the starting point for capacity costs, (that is, dollars per kilowatt), all currently announced large-scale plants expected to be working by 1960 are considered (Table 1). Their capacities (*1*) and the most recently revised estimates of their costs (*4, 7*) are listed, and from the totals given, a capacity cost of about $450 per kilowatt, on the average, is derived.

Referring now to Fig. 2, we see, using point *A* (847,000 kilowatts and $450 per kilowatt in 1960) as the origin of the upper cost line, that this line intersects the 100,000 kilowatt capacity line at $950 per kilowatt. This can be taken to refer to the Shippingport plant, which is expected to cost about $700 per kilowatt. Accordingly, a second line, parallel to the first, was drawn through this value to indicate a lower possible cost range.

A similar procedure was used in obtaining the two bus-bar cost lines. Point *B* was obtained from the data given in Table 2. Fixed costs are computed by taking 10 percent per annum of the $450 per kilowatt investment cost and then converting to mills per kilowatt-hours by noting that in recent years the ratio of kilowatt-hours to kilowatts has remained steady at about 4500 for the whole utility industry (*8*). The lower cost line was similarly derived, except that the maximum McKinney panel figures of 4 and 2 mills, respectively, were used for fuel and operating costs and the figure 15.5 mills, based on $700 per kilowatt (1958), was used for fixed costs.

As noted, Fig. 2 also indicates when these power levels and, hence, these costs will be applicable. Recent evidence indicates, moreover, that these predictions may be quite realistic. Sir John Cockroft (*9*) has estimated that British nuclear power would cost 8 mills per kilowatt-hour in 1960 and that U.S. costs would be about 50 percent greater—that is, 12 mills per kilowatt-hour. This is point *C* in Fig. 2, which is seen to fall within the range of the estimate. Similarly, Untermyer (*10*) has cited the experience of the 5000-kilowatt plant of the General Electric Company in Vallecitos, California. Costs there were about $600 per kilowatt at nominal capacity, but the plant could be operated at up to double load if its A.E.C. license permitted; hence this figure must be regarded as an upper limit. Even so, $600 per kilowatt in 1957–58 is well below the lower cost line (point *D*). The nuclear cost levels must now be set against cost developments in conventional power.

Projection of Conventional Power Costs

Present conventional steam power costs are about $150 per kilowatt capacity and the mills per kilowatt-hour range from about 4 to 10 in most cases, being distributed in a rather skewed fashion between these limits, with the mode (that is, the most common level) at about 4.5 mills (*11*).

Both Davis and Roddis (*1*) and the

Table 2. Computation of point B, Fig. 2 (*2*).

Item	Cost (mills/kwh)
Fuel	3.5
Operating and maintenance	1.1
Fixed costs	10.0
Total	14.6

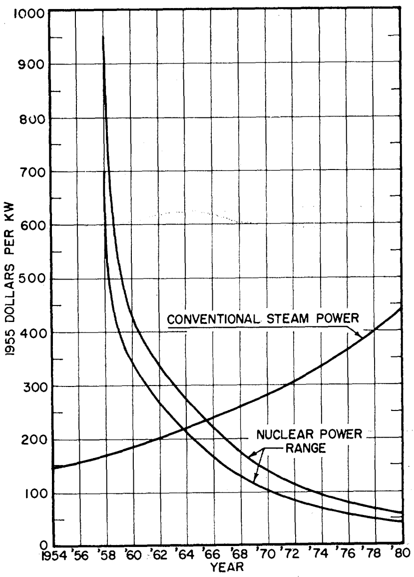

Fig. 3. Projected alternative power costs, 1955–1980.

McKinney panel (*2*) expect this cost pattern to continue. There is recent evidence, however, which calls into question the validity of this estimate. In a study of central station steam equipment costs, Watkins (*12*) has developed a method for predicting the requirements in decreased station heat rate which must be met in order to keep future power costs at their present level. From this, it is found that, in order to maintain present costs through 1967, a net steam rate efficiency gain of 3000 British thermal units per kilowatt would have to be realized. However, the McKinney panel expects an improvement of only about 800 British thermal units per kilowatt in that period, which, according to Watkins, would be just sufficient to neutralize a very modest concurrent rise in fuel costs from $6.25 to $7 a ton. Boiler costs may therefore rise to $6 per pound of steaming capacity as compared with $3.57 in 1955. Boiler costs are a key determinant of power plant cost, and this factor may therefore be applied to all elements of the investment need, particularly since other equipment must be suitable for operation at the same pressure, temperature and efficiency level as the boiler and therefore follows a similar cost structure. Accordingly, the investment cost in 1967 may be expected to be

$$\$150 \times (6/3.57) = \$252 \text{ per kw}$$

Bus-bar costs are currently made up of 54 percent fixed charges, 36 percent fuel cost, and 10 percent operating and maintenance (*6*). Applying these percentages to the 4.5-mill-per-kilowatt-hour rate, we get the breakdown given in Table 3.

The range will be from 5.75 to 14.35 mills per kilowatt-hour, obtained as in the table. The operation and maintenance cost is expected to increase in accordance with the observed increase in average hourly earnings, according to data of the Bureau of Labor Statistics. The values were extrapolated to 1980.

Watkins' analysis also points out that, in order to keep within these costs, further rises in unit size, operating temperatures, and pressures must be countenanced and that size, particularly, is likely to present major operating and power market problems. The 750,000- or 1-million-kilowatt units envisaged in this connection would be too large, relative to total system capacity, for any but the largest half-dozen utilities in the country. Even there, present restrictions on the relation between largest single units and system capacity would have to be revised upward. This has not been specifically considered here, but it seems probable that, since not all conventional plants of 1967 will be able to be of this "optimum" size, many will be more expensive still. Watkins' data for boiler and equipment cost and, in fact, a study of recent trends of machinery prices suggest that this viewpoint may prove correct.

Comparison of the Two Methods

It is now possible to summarize the results of the computations and thus to compare the cost projections for the two methods of power generation. Figure 3 indicates projected movements of the costs of power station capacity, and it will be observed that the break-even zone

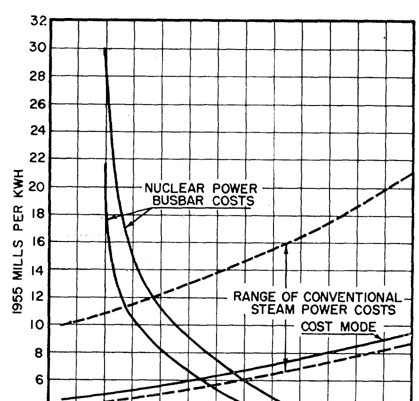

Fig. 4. Projected alternative power plant capacity costs, 1955–1980.

Table 3. Typical present costs for conventional steam power production and projections for 1967.

Item	Costs, 1958 (mills/kwh)	Anticipated fractional increase	Costs, 1967 (mills/kwh)
Fixed charge	2.43	6/3.57	4.08
Fuel	1.62	7/6.25	1.82
Operation and maintenance	0.45	155/124	0.56
Totals	4.50		6.46

occurs between 1964 and 1966. Figure 4, on the other hand, shows power costs in mills per kilowatt-hour, and it is seen that the break-even zone is much wider. The cost range of conventional power, as illustrated, is largely due to fuel cost differentials, though, as noted, economics of scale is becoming an increasingly great problem in some areas. At any rate, it appears from Fig. 4 that, beginning in 1960, nuclear power will begin to compete with conventional plants of high cost and that, by 1968, even the highest cost of nuclear power, as projected here, will be about the same as the lowest costs of conventional steam power in that period. It will also be observed that in this analysis there actually is a break-even point and that nuclear and conventional steam power will not enjoy a prolonged period of equality of cost. Such predictions of sustained cost equality have also appeared in other estimates of nuclear and conventional power costs (*1, 2*). The method used here, however, points to an early and sharp cost distinction favoring nuclear power.

In Fig. 2, on which the present estimates of nuclear power costs are based, a certain rate of nuclear power introduction was used which is part of a rather more conservative forecast than the present one. It may be that, if the cost trends illustrated here hold true, the rate of introduction and of contribution to United States power needs may actually be more rapid than is here indicated, particularly in the latter part of the break-even zone of Fig. 4. This, in turn, might have the effect of accelerating the cost decline.

It may be objected that the converse also holds true—that if, for some reason, the introduction of nuclear power in the United States were to proceed at a much slower rate than that predicted by Davis and Roddis, the costs would also decline more slowly. This, however, fails to take into account the fact that technology is indivisible and international and that the large-scale work on power reactors now in progress, especially in Europe and the U.S.S.R., will bring with it declines in costs quite similar to those illustrated here. In the case of Europe, rising costs of coal and reluctance to depend on Middle East oil furnish powerful incentives for introducing nuclear power. Thus, Cockroft's cost prediction, already cited (*9*), actually means that in England nuclear power will cost about 10 percent more than the national *average* in 1960, the same in 1963, and 30 percent less by 1970. This timing is quite similar to that illustrated in Fig. 4.

Any substantial acceleration of atomic power usage by the early 1960's would actually require advance planning now. This does not appear in the offing, however, judging from current rather "bearish" industry comments in the technical press. It would seem, then, that we may anticipate a gradual increase in the real cost of power, followed eventually by a decline, as nuclear power really effects its commercial "breakthrough."

In the present analysis, only steam-cycle nuclear plants have been considered. No attempt has been made to estimate the costs of direct generation fission plants or of fusion power, which would probably also circumvent the steam cycle. Their feasibility is as yet not proven but, especially in the case of fusion power, may well be demonstrated in time to hasten the demise of the coal-fired steam plant even more.

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Albert Prescott Mathews, Biochemist

The death of A. P. Mathews in his 86th year, on 21 September 1957, has removed one of the last of those American scientists who came under German influence during the latter part of the 19th century. Although Mathews was granted his Ph.D. degree by Columbia University in 1898, he had previously (1895–1897) studied and traveled in Europe. At Marburg, he came under the influence of the German biochemist and Nobel prize-winner Albrecht Kossel, who greatly stimulated him, arousing his interest in the nucleus and in the physicochemical aspects of biology.

Mathews' early work had to do with the physiology of secretion, but he soon turned to a more general study of living cells. As a research scientist, Mathews published about one hundred papers on a wide variety of biochemical and biophysical subjects. Of his five books, three are biochemical in content—*Physiological Chemistry* (1915), *Principles of Biochemistry* (1936), and *Vitamines, Minerals and Hormones* (1937). The other two—*The Nature of Matter, Gravitation and Light* (1927) and *Gravitation, Space-time and Matter*—show his interest in philosophical subjects, an interest which permeated some of his shorter works. The book on *Physiological Chemistry,* first published in 1915, was the principal American text for nearly three decades. The sixth revised edition appeared in 1939. It not only served to present the properties of the chief groups of biochemical compounds but approached the subject from the viewpoint of the physical chemist. The book appeared at just the right time to inspire many a student to decide on a career in this rapidly growing and important subject.

Mathews was born in Chicago on 26 November 1871. His choice of biochemistry for a career was not a result of an early interest in either biology or chemistry. His father was a writer and music critic for the old *Chicago Daily News* at the time the paper was edited by Melville Stone, and Eugene Field, the poet, was a columnist. From his early years, Mathews was exposed to the best in music. As a very young boy he was taken to concerts and to the opera by his father, and he thus developed a taste for and love of music, which gave him the greatest pleasure in later life. Many of his friends were not aware of this aspect of his character but thought of him as being purely a scientist, a teacher, and a philosopher.

Mathews finished high school at the age of 15 and was ready to enter the Massachusetts Institute of Technology, where he intended to study electrical engineering. At M.I.T. he came under the influence of William T. Sedgwick, whose textbook *General Biology,* written in collaboration with E. B. Wilson, first appeared in 1886 and was widely used in schools and colleges. This influence undoubtedly changed the direction of Mathews' career from the purely physical to the biological sciences. He was no doubt influenced by his grandfather, a physician, with whom he spent his summers. The two discussed medical problems, and young Mathews went the rounds of patients with his grandfather. Thus, his medical, biological, and chemical interests, and his strong leaning toward physical chemistry determined that Mathews should become, first, instructor and then assistant professor at the Medical School of Tufts College, later at Harvard Medical School. He went to the University of Chicago in 1901, finally becoming head of the department of physiology, later head of physiological chemistry, a position that he held from