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Electric utilities, reactor designers and builders, and the federal government have badly underestimated the costs of new nuclear power plants over the past fifteen years. Although not all of the increases were readily predictable, particularly those caused by rapid general inflation, nuclear advocates failed to foresee most of the sixfold growth in real costs resulting from new reactors' greater complexity, scope, and regulatory surveillance.

This review recounts the methods used by nuclear power proponents to convince policymakers, the public, and themselves that new nuclear plants would be competitive with other energy sources, long after conclusive contrary evidence was available. It shows that the technique of "engineering estimation" relied upon by government and industry officials was singularly unsuited to predicting costs for an immature technology subject to changing regulation and overseen by mediocre management.

Industry conventions against expressing costs in real terms (constant dollars) further disguised the extent of cost escalation and impeded the application of empirical data in predicting future costs. Rigorous statistical examinations showing reactor cost growth far outstripping both overall inflation and coal-fired electricity costs were performed by outside analysts only. Failure to heed such findings has contributed to billions of dollars of excess investment in new nuclear projects, like Seabrook, being built by fifteen New England utilities.

The article concludes with suggestions for improving future estimation of nuclear power costs, and an appeal for institutionalizing countervailing economic assessments of large capital investment projects.

THE ECONOMIC FORTUNES of nuclear power in the United States have steadily worsened over the past fifteen years, going from promising to marginal to calamitous. Among the new generation of U.S. nuclear power plants—the fifty-odd reactors finished, cancelled, or still under construction after 1982—no more than a handful will produce economical electricity. The aggregate monetary damage from the remaining plants may reach $100 billion,[1] and utility investors, customers, and regulators are already warring over who will bear the costs.

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How could such massive waste occur, particularly in a country noted for efficient capital allocation? The answer to this question is complicated; no explanation is uncontroversial. But a careful look at the cost-estimation process of the nuclear industry and the federal government in the 1970s and 1980s will show "systematic confusion of expectation with fact," as one observer has described it, and steadfast denial of adverse cost experience.

The Heart of the Nuclear Cost Predicament: Skyrocketing Capital Costs

Nuclear power's cost problem in the United States is rooted in the astonishing increase in reactor "capital costs"—construction costs plus related financing costs. Nuclear plants being finished today are costing fifteen to twenty times as much as reactors built in the early seventies: $3 billion to build a typical thousand-megawatt reactor now, versus $150 to $200 million then. The real increase, with inflation factored out, is about sixfold.

As nuclear capital costs began rising in the seventies, predicting them became central to the debate over the economics of building new plants. In this debate, the prime benchmark for nuclear costs was concurrent coal-fired electricity—a pragmatic standard, yet a myopic one. On the one hand, coal-fired plants already produced half of the nation's power, and limits to domestic oil and gas resources made coal the only nonnuclear fuel suitable for new, conventional central-station generating plants. Nuclear/coal comparisons were also simple and familiar to utility planners. On the other hand, by insisting that large, central generators were the only viable means of servicing electricity requirements, the power industry effectively ignored alternatives such as cogeneration, renewables, and improved energy efficiency. Today, after considerable advocacy and development of new analytical tools by environmentalist organizations, the alternatives have moved to center stage in informed electricity policy-making.[2] But insofar as the nuclear/coal framework dominated the nuclear economics debate over the past decade—the focus of this paper—I adopt it here.

While the comparison of nuclear- and coal-generating costs hinges on capital costs, it must also subsume costs for maintenance, repairs, outages, decommissioning, and fuel, nuclear's strong suit. It is helpful to distill assumptions about these costs into a "break-even" capital-cost ratio, denoting how large a capital cost handicap nuclear plants can offset through fuel savings. Although geographic differences in coal prices imply region-specific break-even ratios, a "national average" break-even ratio is a useful construct. Depending on the analyst's view of cost factors such as the nuclear plant's capacity factor and the coal plant's fuel cost, the break-even capital cost ratio has generally stood between 1.2 and 1.4, meaning that nuclear plants could stand a 20 to 40 percent higher capital cost than coal plants and still end up equal in lifetime generating costs.

The Empirical Evidence

In what became a widely quoted statement, Harvard Business School Professor I. C. Bupp wrote in 1978, "Systematic confusion of expectation with fact, of hope with reality, has been the most characteristic feature of the entire 30-year effort to develop nuclear power. . . . The distinction between empirically supported fact and expectation was blurred from the beginning in the discussion of nuclear power economics. . . . [W]hat was missing . . . was independent analysis of actual cost experience."[3]

Bupp was decrying the failure of nuclear promoters to reconcile their estimates of future plant costs with empirical data, or even to distinguish between the two. This failure persists even today. Only four comprehensive studies of U.S. nuclear capital cost experience have been published. Three, produced independently of the nuclear industry, found that cost trends were running against nuclear power; the fourth, sponsored by nuclear utilities, seemed constructed deliberately to thwart the drawing of any conclusions at all.

The three independent studies measured nuclear and coal capital cost trends from the costs of completed plants. Bupp's Harvard-M.I.T. team found in 1974–75 that nuclear capital costs had increased two to three times faster than coal plant capital costs between the late 1960s and mid-1970s.[4] William Mooz of the Rand Corporation demonstrated that the sharp increases in real reactor costs in the first half of the 1970s continued with no letup in the second half.[5] My work between 1979 and 1981 showed that the average ratio between nuclear and coal capital costs increased from just over 1.0 at the start of the 1970s to over 1.5 at the end of that decade, even counting expensive pollution control devices such as sulfur dioxide scrubbers in the later coal plant costs. I also identified divergent nuclear and coal regulatory trends portending that the capital cost ratio would climb much higher, to a range of 1.75 to 2.65 for plants finished in the mid- to late 1980s.[6]

Empirical data are validating this forecast. The nuclear/coal capital cost ratio for plants built in the 1980s is averaging between 2.0 and 2.5, far beyond the 1.2 to 1.4 break-even range—the capital cost ratio at which nuclear and coal generating costs are equal.[7]

Nuclear power interests haven't so much rebutted these empirical analyses as ignored them, partly by sending up a smoke screen of studies favorable to nuclear power. These studies have been largely of two types: compilations of current coal and nuclear generating costs, with the sample of plants selected to put the best possible face on nuclear power; and "engineering estimates" that disregarded mounting regulatory and construction problems in forecasting reactor costs. The most influential of these studies are discussed below.

Put Your Best Foot Forward: The Atomic Industrial Forum Surveys

The annual surveys of the U.S. nuclear trade group, the Atomic Industrial Forum (AIF), purport to measure the current cost of electricity from nuclear, coal, and oil plants. Until recently, they obligingly found nuclear-generated electricity to be cheapest. For example, the AIF survey of 1978 costs put the average generating cost—fuel, operations, and capital charges—at 1.5 cents per kilowatt-hour (kwh) for the nation's nuclear plants and 2.3 cents/kwh for coal plants.[8] These figures, and similar ones for other years, were disseminated by the AIF, the Edison Electric Institute, and many utilities, and were widely reported by the press.

Two objections were raised to these surveys. First, they obscured emerging cost trends by lumping together economical early reactors with uneconomical later ones. Worse, although the surveys professed to be comprehensive, the samples were badly skewed to favor nuclear power. Twelve of the fourteen most expensive U.S. nuclear plants were omitted from the 1977 and 1978 surveys, as publicity-shy owners of expensive reactors withheld data. In addition, owing to a survey convention that limited the comparison to utilities with *nuclear* plants, only a small fraction of U.S. *coal* plants were included, and these tended to be above average in cost (since utilities build fewer reactors where coal is cheaper).

After considerable criticism,[9] the AIF broadened its nuclear samples (but not coal). However, in order to elicit cost data for expensive reactors, the surveys stopped grouping costs by utility. This precludes checking individual plant data—an important limitation in light of arithmetic inconsistencies in some AIF surveys and the inherent complexity of much of the cost data. Indeed, the current surveys are mere one-page press handouts, yet the AIF and other nuclear promoters represent them as in-depth evaluations of comparative costs.

Don't Look Back: The Department of Energy Estimates

For all their biases, the AIF surveys have not been nuclear promoters' most insidious misrepresentations of reactor costs. That distinction falls to a fifteen-year series of reports prepared for the Atomic Energy Commission (and its successor, the Department of Energy [DOE]) by Philadelphia-based United Engineers & Constructors (UE&C).[10] These reports have formed the basis of the federal government's pronouncements on the economics of nuclear power since 1968, and they have had a profound influence on U.S. energy policy and utility investments.

The DOE reports rely on a procedure known as *engineering estimation* to predict future nuclear and coal plant costs. This technique first develops a conceptual plant design based on a scope of work that is predicated on an assumed set of safety and environmental requirements. It then calculates the labor, materials, and equipment needed to fulfill the design and applies estimates of wage rates and material costs to compute the total charges. Contingency allowances, typically 10 to 15 percent, are added to cover new safety criteria, strikes, delivery delays, or other problems likely to crop up in big construction projects.

Engineering estimation has failed spectacularly at nuclear plants, however. Since the early 1970s, the inflation-adjusted capital costs of new plants have risen an average of 14 percent each year, consuming *annually* contingency allowances intended to cover a project's *whole construction lifetime*. The root cause has been new and more stringently applied safety requirements that have expanded the scope of projects during construction, together with failure to manage construction to accommodate the increased stringency.

Yet DOE's hindsight has been no better than its foresight. The department has never retrospectively compared its nuclear cost forecasts to actual reactor costs, or otherwise acknowledged the persistent gap between its estimates and reality. Instead, DOE analysts endlessly fine-tuned their elaborate computer model that varied capital costs according to almost every conceivable assumption—geographical location, cooling tower type, turbine configuration, etc.—except for the conditions that were driving reactor costs sky-high: unstable regulatory requirements, changing designs, and outmatched construction management, conditions well documented elsewhere by DOE's own cost contractor, among others.[11] Using this model, for example, DOE estimated in 1977 that reactors completed in 1986 would cost a mere $1.1 billion per thousand megawatts of capacity—half of what 1985-87 plants are actually costing, after netting out differences between expected and actual interest and inflation rates.

The DOE reports also overstated coal capital costs, contributing further to inaccurate perception of nuclear power's competitiveness. For most of the 1970s, DOE and other nuclear proponents assumed that costs of SO_2 scrubbers and other pollution controls needed at new coal plants would match growing nuclear safety requirements, keeping future coal plant costs close to those of new reactors. In fact, nuclear safety rules proved far costlier than coal emission controls, and the average ratio of completed nuclear to coal capital costs grew from 1.05 in 1971 to 1.5 in 1978, even with scrubbers.

DOE's most egregious misestimate of relative nuclear/coal capital costs came in 1980, when it doubled its 1978 nuclear and coal cost forecasts. This was appropriate for nuclear plants, which faced regulatory impacts from the 1979 Three Mile Island (TMI) accident, along with record inflation and interest rates. Yet coal plants faced no new regulatory constraints that weren't already reflected in DOE's 1978 forecasts. Although empirical evidence indicated otherwise, nuclear promoters continued to insist that coal's regulatory burden and capital cost escalation were as severe as nuclear power's.

The 1980 report, with an implied *future* ratio of nuclear to coal capital costs no greater than the 1.5 to 1 ratio for plants *completed* in 1978, was especially fateful. Utilities and DOE used it to reassure wavering utility regulators and investors that besieged reactor construction ventures were still worth completing. These reassurances have since proven hollow for investors whose capital is at risk in several dozen expensive reactor projects, and for regulators who are now walking the edge between utility insolvency and sharp rate increases.

DOE's 1982 estimates implied a nuclear/coal capital cost ratio of 1.6 to 1.7, which also lagged far behind changing costs. Yet these estimates remain the basis of DOE's conclusion that nuclear plants ordered in the 1980s and finished in the 1990s will be competitive with coal.[12] In fact, reactors being finished in the 1980s are averaging at least twice the capital costs of new coal plants and will probably average between 70 and 80 percent higher lifetime generating costs.[13] Nevertheless, DOE's optimistic conclusion is widely cited, particularly in international evaluations of nuclear power, as an authoritative portrait of relative nuclear/coal costs in the United States.[14]

DOE's estimator United Engineers, for its part, has begun—a decade late—to back away from its insistence that nuclear power's precipitous capital cost escalation is no different from that for coal. "Recent information on material and labor requirements," admitted UE&C's chief cost estimator in 1982, "indicate[s] that a . . . higher rate of cost increase may be appropriate for nuclear plants."[15]

Confusing Time with Costs

Throughout the late seventies and early eighties, while rising costs and the TMI accident were prompting outsiders to look critically at reactor economics, the power industry continued to rehash its engineering estimates of capital costs. These estimates were divorced from nuclear power's deep-seated regulatory and construction problems and oblivious of the widening nuclear/coal gulf. World-leading reactor constructor Bechtel projected a 1.21 nuclear/coal capital cost ratio just before TMI, increasing only to 1.25 afterward.[16] The Committee on Nuclear and Alternative Energy Systems of the National Academy of Science, a senior nuclear-industry panel cast as impartial "scientists," predicted a range of ratios between 1.0 and 1.25.[17] As recently as 1982, the year the *Wall Street Journal* coined the expression "rate shock" to describe the cost impacts of new nuclear plants, architect-engineer Sargent & Lundy was still forecasting a capital cost ratio under 1.5.[18]

Many of these sources seized on shortening reactor construction periods as the means to control costs. Studies by Sargent & Lundy in particular featured painstaking calculations of the potential savings from compressing licensing and construction times.[19] Yet most of these savings are illusory, for they are won by making ratepayers pay for the power plant sooner. The use value of money forfeited by ratepayers offsets the savings from curbing compounding interest during construction, as simple arithmetic demonstrates. At 10 percent interest rates, for example, ratepayers are no better off with a $3.0 billion reactor finished (and entering rates) today than with a $3.3 billion plant finished a year from now.[20] Yet in power industry parlance, the earlier plant is 10 percent cheaper.

The utility industry's Electric Power Research Institute (EPRI) has also been sidetracked into the construction duration issue. It published a major empirical study of power plant "lead times" in 1983 but has shied away from analyzing empirical plant *costs*. Its assertion that "time-related costs represent a large fraction of the total capital costs of most large projects"[21] also shows a failure to appreciate that time-related costs are primarily interest and inflation, which evaporate when the time value of money is considered. (The EPRI study did break with industry dogma to conclude that coal-plant licensing and construction periods were shorter and more predictable than for nuclear plants, however.) In the same spirit, the nuclear industry has all but canonized the St. Lucie 2 reactor for its completion in 1983 in a little over six years, ignoring a number of its slower-built contemporaries with lower real costs. River Bend, also considered successful for its below-average construction time, actually has the industry's fourth largest per kilowatt (kw) real cost.

Lonely at the Top: Commonwealth Edison's Nuclear Program

Chicago-based Commonwealth Edison, the nation's largest reactor operator and builder, is also the industry's most vocal champion of nuclear power. A 1978 Edison article in *Science* touting the roughly 40 percent savings over coal for the company's six large nuclear units helped shore up support for nuclear power in the academic and scientific communities.[22] However, the comparison was biased by Edison's excess capacity, which leads it to operate its coal units part-time, thereby inflating their per-unit fixed costs. The remaining savings were also peculiar to Edison, insofar as its nuclear units cost only half as much as the U.S. average (four were built as loss-leaders by General Electric), while the company's coal fuel costs were well above those for most other utilities.[23] The article's cost predictions for Edison's 1980s nuclear units were also strikingly inaccurate, underpredicting their real costs by at least a third.[24]

The Chameleonlike Dr. Perl

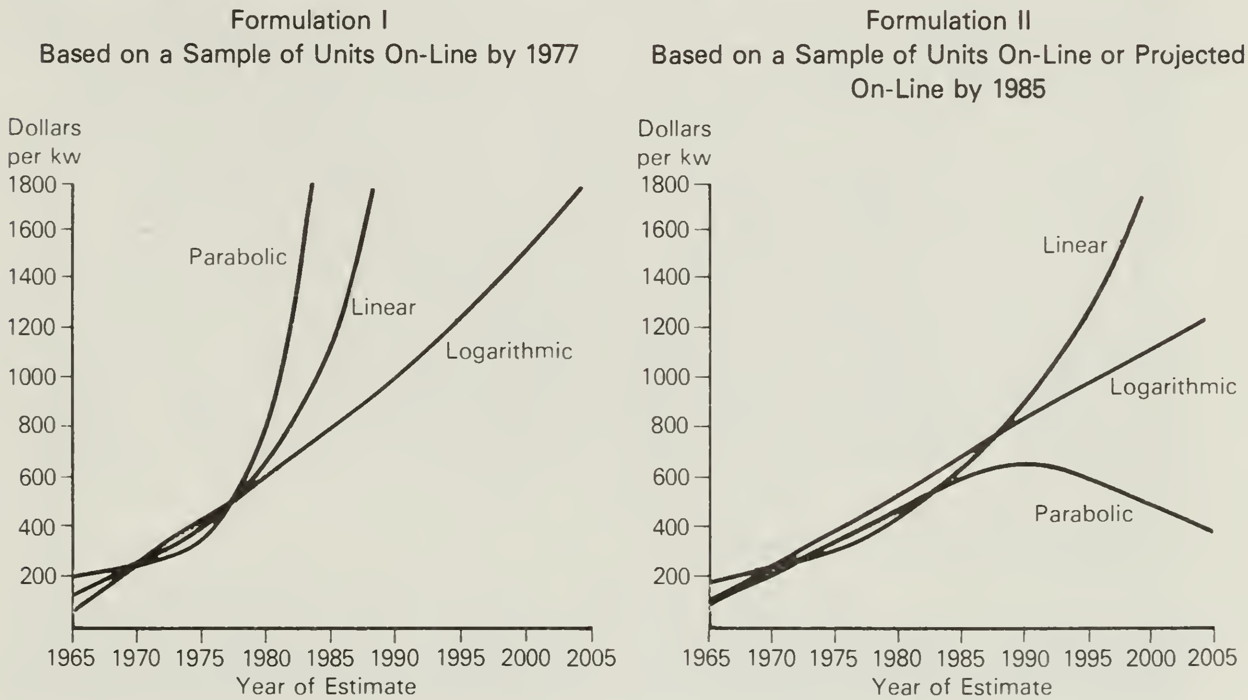
The power industry's only empirical analyses of nuclear and coal capital costs to date have been those by Lewis Perl of National Economic Research Associates (NERA), a leading utility consulting firm. Like Bupp, Mooz, and myself, Perl found in statistical terms that real nuclear capital costs increased rapidly during the seventies. However, Perl rejected extrapolating further increases into the eighties, arguing that the upward slope in historic costs could be read statistically as the temporary growth phase of a cyclical process.[25] Instead, Perl put forth a "fall-back" view in 1978 that future nuclear plants (and coal plants as well) would have the same real costs as recently completed plants, implying only a 1.44 nuclear/coal capital cost ratio.

What Perl represented as reasoned conservatism may in fact have been artifice to bolster NERA's many utility clients, whose nuclear construction programs he has defended before numerous state regulatory commissions, both prospectively, in the 1970s, and retrospectively after the programs soured, in the 1980s. For Perl calculated his capital cost trends from a hybrid data base that blended actual costs of plants completed through 1977 with *utility estimates* for plants *under construction* through 1985. It was classic circular reasoning: by introducing utility underestimates of future nuclear costs, Perl diluted the upward trend in completed reactor costs to permit the inference that nuclear cost growth might stop.

Perl couldn't avoid predicting further nuclear cost escalation in the one instance in which he drew trends from completed plant costs only, in a talk to energy economists in early 1978. There, all of his statistical formulations of historical reactor costs pointed unmistakably upward, and much more steeply than the corresponding coal plant curves, as shown in figure 1. This formulation could not have been salutary to NERA's utility clients, and it was subsequently withdrawn.

Figure 1

Nuclear Construction Costs as Estimated by Three Regression Forms Which Vary with Respect to the Treatment of Time (Dr. Perl)



The two graphs show Dr. Perl's formulations of projected nuclear capital costs as presented in a talk to the Eastern Economics Association in April 1978. Formulation I was based on actual costs of plants finished by 1977. The sample for Formulation II included costs for this first group of plants *plus utility estimates of costs for plants under construction.* In both formulations, Perl projected future reactor costs with three different mathematical forms, as shown. Where only empirical data were used, in Formulation I, all three curves point sharply upward, indicating continuing cost increases. In Formulation II, however, all three cost curves, especially the parabolic, were "pulled down" by the utility estimates, enabling Perl to argue that the direction of future nuclear costs was indeterminate. Projecting future data from estimates about the future is clearly untenable, yet Perl has used Formulation II exclusively since late 1978. He has never published the April 1978 paper from which these two figures were drawn.

The New England Experience

New England has been no exception to the nationwide failure to anticipate uncontrolled growth in reactor costs. All six New England states face considerable losses from utility overinvestment in nuclear power.[26] In mid-1985, the Millstone 3 and Seabrook 1 nuclear power units were estimated to cost $4 billion and $4.5 billion, respectively. That is twice the maximum cost at which the reactors could compete with coal, and still further beyond the cost to break even with cheaper alternatives such as Canadian hydroelectricity, cogeneration, or conservation.[27] Another $1 billion has been expended on Seabrook 2, effectively abandoned in 1984. Full recovery of these costs in rates would cause average electric rates to double for some of the participants and to rise at least 15 percent across New England as a whole.[28]

The misestimation of costs has been more severe at Seabrook, which was begun several years later than Millstone and until recently lagged behind it considerably in sunk costs, making cancellation more feasible. Greater realism about Seabrook's ultimate cost might have resulted in cancelling it in the early eighties, at a savings of several billion dollars. Yet, as late as 1982, an informed comparison of the Seabrook estimate to other plants indicated that the utilities were underestimating Seabrook's cost by almost half.[29] This was not understood by utility regulators and investors—or probably even by the utilities themselves—in part because their comparisons were expressed in "nominal" or "mixed" dollars that grossly overstated the effect of inflation and interest costs for late plants such as Seabrook. Thus, while the 40 percent increase in the Seabrook estimate in late 1982 may have appeared a sufficient correction, it largely reflected inflation and interest for the ten-month schedule delay and included only a fraction of the real increase needed to match the costs of comparable nuclear facilities. The perception that the new estimate was in line with industry experience was a delusion.

An Agenda for Nuclear Economics

Developing more rounds of nuclear capital cost estimates and comparisons would seem pointless, at least until such time—if that time should ever come—that nuclear power's institutional and technical status can be clarified so that cost estimates may be grounded in reality. Nevertheless, because nuclear power boosters show no inclination to wait,[30] the following guidelines for future efforts in nuclear power economics are offered.

First, nuclear and coal costs must be weighed not only against each other but against the full spectrum of available electricity resources. This includes cogeneration, renewables, and improved energy efficiency. Orders for cogeneration and renewable capacity have surpassed those for nuclear and coal since 1982, and gains from improved efficiency, while harder to measure, have almost certainly been greater.[31] With "whole system costing" methodologies fully established to evaluate these options, utilities can no longer limit their purview to nuclear and coal.

Second, capital cost data must be expressed in constant dollars, with financing costs added separately. The nominal, "as-spent" dollars in which utilities report nuclear and coal plant costs are a mishmash of interest charges, inflation effects, and real costs having *accounting* but not *economic* meaning.[32] To distill cost trends or draw meaningful comparisons from such data, analysts must first convert them to constant terms, a task which at present often requires extraordinary effort.

Third, nuclear cost predictions should be benchmarked against empirical data (in constant dollars). While each construction project may appear unique to its builders, insightful statistical analysis of industrywide costs has proven successful at extracting cost trends, which can serve as baselines for evaluating estimates of future costs. This is true for coal as well as nuclear plants. Although coal plant designs have remained far more stable, and their costs more amenable to engineering estimates (owing to lower susceptibility to regulatory changes during construction), estimates of future coal capital costs could be made more accurate by reconciliation with empirical data.

Fourth, rising costs for reactor operations, maintenance, and improvements must be reflected in forecasts of future nuclear "life-cycle" costs. O&M costs and capital additions, as these items are known, have also been affected by increased reactor complexity and regulatory stringency, and have grown almost as fast as reactor capital costs since the early seventies. They now average $75 million per year for each thousand megawatts of nuclear capacity, or 3 to 4 percent annually of original construction costs for new plants.[33] Realistic assessments of O&M costs and capital additions are particularly important for weighing the economics of completed or nearly completed reactors, for which most capital costs have already been expended. Yet in shameless repetition of previous mistakes, most nuclear advocates dismiss past escalation in O&M costs and capital additions as a product of "one-time events" and a bygone era of regulatory change, and they project future costs at only half of present levels.

Fifth, differences between estimated future costs and recent cost experience—especially projections that future reactors will cost much less than those just finished—must be fully justified. In particular, expectations that reduced "regulatory turbulence" will cut reactor costs must be fleshed out with analyses of the nature and cost of regulatory impacts. This will require separating the effects of more stringent regulatory criteria from the effects of *changes* in the criteria—a distinction missing in most discussions to date.

The same applies to cost savings that nuclear advocates ascribe to new technologies and standardized designs. Increased use of microprocessors and robotics, and reductions in custom engineering, could conceivably mitigate problems in nuclear (and coal) design, construction, and operation in such areas as accident analysis, regulatory evaluation, quality documentation, hazardous repair, and so on. But hand-waving is not an acceptable way to estimate the savings, especially given nuclear power's long trail of engineering misestimates. The nuclear industry will win a hearing on its hopes for competitive future reactors only by acknowledging the appalling level of current costs, and explaining why its future will differ from its past.

Lessons Learned

What lessons can we learn from the failure of nuclear promoters to represent nuclear costs competently and candidly?

One lesson is that powerful institutions cannot be relied upon to act in their own economic self-interest, let alone in the public interest. In the case considered here—nuclear cost escalation—industry leaders and government planners failed to fully grasp either causes or extent. They excessively blamed the general economic conditions of high inflation and interest rates and overlooked the real increases driven by nuclear-specific problems, namely the safety controversy and technical deficiencies. Nuclear interests insisted that nuclear and coal cost behavior were the same, when in fact nuclear costs were rising at least twice as fast. Examination of actual cost trends might have led utilities to curb nuclear expansion earlier, with savings of tens of billions of dollars. Instead, a pronuclear mind-set blinded promoters to the warning signs, and nuclear power became a victim of its own propaganda.

Another lesson concerns the failure of public or quasi-public institutions to scrutinize the promoters' self-serving estimates and underlying assumptions. Not Congress or its watchdog agencies, not the state utility regulators, not the credit-rating agencies, not the think tanks or universities (with the exception of Mooz at Rand and Bupp's group at Harvard) punctured the industry-government unanimity on nuclear/coal costs until recently. To a disturbing extent, these groups merely repackaged DOE or industry cost estimates, lending them a spurious aura of scholarship. For example, the seemingly authoritative (and favorable to nuclear power) economic evaluation in the 1977 "Nuclear Power Issues and Choices" report by a group of academics convened by the Ford Foundation rested on industry and government engineering estimates;[34] the estimators later cited the report as confirmation of their figures. Much of what appeared as a broad, independently won consensus on nuclear power's cost edge was created with mirrors.

The failure of coal interests to attack nuclear overoptimism is particularly noteworthy, insofar as the two sectors compete for the same electricity market. Unfortunately, overlap among coal and nuclear constructors and vendors, and their common stance as champions of centralized electric generation and opponents of environmental and safety regulation, militated against serious criticism. Indeed, the coal industry used nuclear promoters' exaggerated forecasts of coal pollution control costs to lobby against stringent emission standards. Only after new standards were settled on in 1978 did the coal industry begin distancing itself from those forecasts.

The final lesson, following from the first two, is the need for independent analysis of the economic and societal consequences of major public investments.

The need is hardly confined to nuclear power (a parallel story to this could be told about the utility industry's failings in forecasting electricity usage) or to energy issues. The momentum generated in large undertakings all too easily breeds intolerance of dissenting views, precisely when they may be most needed to correct the enterprise, or to determine whether it is worth pursuing at all. If the unfortunate nuclear power experience helps to institutionalize dissenting views elsewhere, then perhaps the losses will have served a constructive purpose.

Notes

1. This figure comprises $25 billion invested in plants cancelled through 1984; possible future cancellations with $10 to $20 billion already invested; and the $50 billion or more prospective difference between lifetime power costs of reactors being completed and of alternative coal units with advanced emission controls. For more detail, see C. Komanoff, "Where Does Prudence Stop and Waste Begin? U.S. Nuclear Plant Costs in the 1980s," paper presented to the National Association of State Utility Consumer Advocates, 13 August 1984, at Williams College (available from Komanoff Energy Associates, New York).

2. Advocacy of alternative electricity planning has been led for a decade by Amory Lovins (formerly with Friends of the Earth, now with Rocky Mountain Institute, Old Snowmass, Colo.), Natural Resources Defense Council (San Francisco), and Environmental Defense Fund (Berkeley, Calif.). Lovins's *Soft Energy Paths* (Cambridge, Mass.: Ballinger Publishing Co., 1977) was particularly seminal.

3. Irvin C. Bupp and Jean-Claude Derian, *The Failed Promise of Nuclear Power* (New York: Basic Books, 1981), originally published in 1978 as *Light Water: How the Nuclear Dream Dissolved.* The quotes are from pages 188, 47, and 76, respectively.

4. Irvin C. Bupp et al., *Trends in Light Water Reactor Capital Costs in the United States: Causes and Consequences,* CAP 74-8 (Center for Policy Alternatives, M.I.T., Cambridge, Mass., 1974). Abridged in *Technology Review* 77, no. 2 (February 1975): 15–25.

5. William Mooz, *Cost Analysis of Light Water Reactor Power Plants,* R-2304-DOE (1978), and *A Second Cost Analysis of Light Water Reactor Power Plants,* R-2504-RC (1979) (Santa Monica, Calif.: Rand Corporation).

6. Charles Komanoff, *Power Plant Cost Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics* (New York: Komanoff Energy Associates, 1981; republished by Van Nostrand Reinhold, New York, 1982). The statistical findings therein were first circulated in draft form in mid-1978.

7. Comprehensive utility data compiled by Komanoff Energy Associates in mid-1985 indicate construction costs (exclusive of financing) averaging $2250/kw in 1984 dollars for nuclear plants completed or still in construction after 1982, versus approximately $1000/kw for contemporaneous coal plants. Addition of real financing costs would widen the ratio on account of the longer construction durations and higher costs of capital for nuclear units. Data from a year earlier are summarized in Komanoff, "Assessing the High Costs of New U.S. Nuclear Power Plants," *Public Utilities Fortnightly* 114, no. 8 (October 11, 1984): 33–38.

8. Atomic Industrial Forum, *Annual Generating Cost Surveys*, published as annual news releases since the mid-1970s (Bethesda, Md.).

9. Charles Komanoff, *Power Propaganda* (Washington, D.C.: Environmental Action Foundation, 1980).

10. A typical report in the series is U.S. Atomic Energy Commission, *Power Plant Capital Costs: Current Trends and Sensitivity to Economic Parameters,* WASH-1345 (Washington, D.C., 1974). A listing of most of the AEC/DOE reports is in J. H. Crowley and J. D. Griffith, "U.S. Construction Cost Rise Threatens Nuclear Option," *Nuclear Engineering International* (June 1982): 25–28, fig. 2.

11. Ironically, testimony by United Engineers' own manager of capital cost estimation in a New York State Public Service Commission investigation of comparative nuclear and coal costs in 1976 was probably the most articulate statement to that time of the effects of safety-related requirements on nuclear capital costs (J. H. Crowley, direct testimony, Case 26974). Several exhibits in the testimony depicting nuclear power's regulatory burden were reproduced widely, including one charting the rapid growth in reactor safety standards, and another using hypothetical design criteria for a reactor light switch to illustrate the maze of regulations that nuclear designers must negotiate. The testimony also warned, prophetically, that "the regulatory climate is still dynamic . . . the full effect of [regulatory] factors is not predictable, and the current cost estimates and schedule must be qualified as reflecting those criteria in effect as of the end of 1975, with no additional regulatory changes or delays" (p. 31). UE&C's work for the AEC and DOE contained no such explicit warnings, however.

12. Energy Information Administration, *Projected Costs of Electricity from Nuclear and Coal-Fired Power Plants,* DOE/EIA-0356/1 and 2 (Washington, D.C., 1982).

13. See notes 1 and 7.

14. Organization for Economic Cooperation and Development (OECD), *Costs of Generating Electricity in Nuclear and Coal-Fired Power Stations,* ISBN 92-64-12514-0 (Washington, D.C., 1983).

15. Crowley and Griffith, "U.S. Construction Cost Rise Threatens Nuclear Option."

16. W. K. Davis and R. O. Sandberg, *Light Water Reactors: Economics and Prospects* (San Francisco: Bechtel Power Corp., February 1979). Davis, Testimony before the U.K. House of Commons Select Committee on Energy, June 1980.

17. National Academy of Sciences, *Energy in Transition, 1985–2010* (Washington, D.C., 1979), 318.

18. W. W. Brandfon, "The Economics of Nuclear Power," paper presented to the American Ceramic Society, Cincinnati, 4 May 1982; reprinted by the Atomic Industrial Forum (Bethesda, Md., 1982).

19. W. W. Brandfon, *A Comparison of Future Costs of Nuclear and Coal-Fired Electricity* (Bethesda, Md.: Atomic Industrial Forum, November 1984).

20. Affidavit of Charles Komanoff, 23 March 1985, *Supporting Emergency Motion for Stay re Waterford Operating License,* available from Government Accountability Project (Washington, D.C.).

21. Electric Power Research Institute, *An Analysis of Power Plant Construction Lead Times,* vol. 1, EPRI EA-2880 (Palo Alto, Calif., February 1983).

22. A. D. Rossin and T. A. Rieck, "Economics of Nuclear Power," *Science* 201 (August 18, 1978): 582–89.

23. Commonwealth Edison's average delivered cost of coal in 1980, for example, was $1.90 per million Btu, 41 percent above the U.S. average of $1.35. See Energy Information Administration, *Cost and Quality of Fuels for Electric Utility Plants,* DOE/EIA-0191(80), tables 3 and 56.

24. Edison estimated in *Science* that twin 1200-MW reactors would cost $692/kw in 1977 dollars, or $1105/kw in 1984 dollars. This figure included interest, although whether in nominal or constant dollars is unclear. Assuming that interest accounted for 20 percent of the estimate in the article—an arbitrary and possibly low guess—the estimate is equivalent to $884/kw in 1984 dollars without interest. Based on Edison's early 1985 estimates, the company's six 1980s nuclear units will cost an average of $1355/kw in 1984 dollars without interest. My own estimate is somewhat higher. (See Rebuttal Testimony of Charles Komanoff, 20 June 1985, Illinois Commerce Commission, Docket No. 82-0855, available from Business and Professional People for the Public Interest, Chicago).

25. Lewis J. Perl, "Estimated Costs of Coal and Nuclear Generation," paper presented at a seminar sponsored by the New York Society of Security Analysts, 12 December 1978 (New York: National Economic Research Associates).

26. Irvin C. Bupp, "Seabrook: A Case Study in Mismanagement," *New England Journal of Public Policy* (Winter/Spring 1985): 60–71.

27. Prospective buyers for shares of Seabrook 1 during the first half of 1985 bid approximately $1,000/kw of capacity, equivalent to slightly over $1 billion for the entire unit. If a market had been opened for Millstone 3, bids of $1500/kw could have been expected, reflecting the greater likelihood of completion and the greater nuclear experience of Millstone's utility owner.

28. See Charles Komanoff, "Pitfalls in Long-Term Electricity Load Forecasting," outline of paper presented to New England Conference of Public Utilities Commissioners, 14 May 1985, at Newport, Rhode Island.

29. My statistical comparison of Westinghouse-design reactors in the U.S. indicated that the Seabrook estimate was 46 percent "below costs predicted on the basis of prevailing trends," making the estimate "unaccountably low" and "suspect." See Komanoff, "The Westinghouse PWR in the United States, Cost and Performance History," 1982, page 6n.

30. See note 19, for example.

31. Christopher Flavin, *Electricity's Future: The Shift to Efficiency and Small-Scale Power* (Washington, D.C.: Worldwatch Institute, Worldwatch Paper 61, 1984).

32. See note 7.

33. Pioneering work in nuclear O&M and capital additions costs by Energy Systems Research Group (Boston) is described in any recent ESRG testimony on nuclear matters.

34. S. M. Keeny, *Nuclear Power Issues and Choices: Report of the Nuclear Energy Policy Study Group* (Cambridge, Mass.: Ballinger Publishing Co., 1977). While the report cited my 1976 estimates of capital costs, those were developed prior to my original capital cost research and were simply derived from DOE estimates.