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What History Can Teach Us about *the* Future Costs *of* U.S. NUCLEAR POWER

Past experience suggests that high-cost surprises should be included in the planning process.

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In response to energy security and environmental concerns, the U.S. is collaborating with nine other countries to develop fourth-generation nuclear reactor technology, which is intended to be safer than current reactors, be available at lower total cost, and incur financial risks no greater than those for other energy technologies. In this article, we discuss the financial risks for new nuclear power to achieve its cost objectives, from a three-decade historical database of delivered costs from each of 99 individual U.S. nuclear reactors. We argue that past technology development patterns indicate the importance of including high-cost surprises in the planning process.

One hundred and four nuclear reactors provided 19.3% of U.S. electricity generation in 2005, but no new reactors have been approved for construction by the U.S. Nuclear Regulatory Commission (NRC) since 1978. Rising and volatile petroleum prices, geopolitical conflicts in fossil-fuel-rich regions, increasing energy demand from emerging economies, and climate change have all contributed to a resurgence of interest in nuclear power because of its potential to address energy security without emitting CO_2 or regional pollutants (*1–5*). Yet questions linger about waste management and proliferation (*6*), and even in a carbon-constrained world, nuclear power may be more expensive than some decentralized energy-efficient and distributed-generation technologies (*7*). What is universally agreed upon is that the role nuclear power will play in our energy future will be shaped, critically, by the framing of debate, the process of evaluation, and the thoughtful integration of this discourse into eventual policy choices (*8*).

For nuclear power to play a significant role in addressing future energy needs, countries must build new reactors to replace those ending their service life and to expand significantly the number of commercial reactors in service. Our 60-year experience with nuclear energy has underscored that future policy formulation requires an estimate of future nuclear energy costs, benefits, and risks as well as recognition of the complex technical and social factors that influenced the costs of the current nuclear fleet. To contribute to this evaluation, we describe a new database assembled from the actual plant-by-plant data from U.S. nuclear power costs, illustrate a pattern of high-cost surprises that is consistent with findings in other statistical studies of extreme values, and argue that the discussion of future nuclear power should delve deeper into whether next-generation reactors might experience similar surprises.

Future reactor design

In response to the public policy goals described earlier, a variety of research and policy teams have conducted assessments of nuclear energy's future potential (*9*, *10*) and outlined plans for both incremental and fundamental changes to nuclear reactor design to increase safety and decrease costs (*11*). The new reactors would therefore encompass improved designs derived from the Generation III+ (Gen-III+) machines in the near term and more radical Generation IV (Gen-IV) designs in the medium term. The U.S. Energy Policy Act of 2005 and the Advanced Energy Initiative of 2006 seek to encourage this development by providing incentives for new plant construction, fast-track licensing, liability protection, and research and development incentives to the industry. As of October 2006, 44 operating licenses for existing reactors had been renewed, 10 were under review, and 17 more applications were expected to be submitted by 2010 (*12*). Nuclear operators have, moreover, submitted their intent to file applications for approval for at least 27 new Gen-III+ reactors (*13*).

Finally, the U.S. and its international partners have for several years been conducting an extensive planning process focused on the implementation of simplified reactor engineering, passively safe and proliferation-resistant reactor designs, and design standardization within Gen-IV nuclear plants. Six different reactor designs are under development, and several seek to diversify beyond standard light-water uranium reactors, for example, by incorporating gas, liquid sodium, or lead cooling and drawing from a larger set of possible fuel cycles (*11*). In each area of design, goals were set to be significant advances over the current fleet of pressurized water reactors (PWRs) and boiling water reactors (BWRs) in the U.S. The forum has, moreover, adopted explicit financial goals: first, to have a lower lifetime levelized cost than other energy sources; and second, to achieve a level of financial risk comparable with other energy projects.

Nuclear cost risks

Despite these goals, past experience with such large-scale technological ventures highlights linked policy, cultural, and economic challenges, some of which may not be amenable to technological solution (*14*). In the past, U.S. nuclear reactors depended not only on the economics of power generation but also on the risks of capital cost escalation, the importance of operational learning, and the idiosyncratic problems of large-generation resources whose site characteristics do not allow for mass production (*15–17*).

One way to understand the cost risks within this new deployment of nuclear reactors is to investigate the cost distribution of their nearest technological relatives, the current generation of nuclear reactors. The record of costs for the emergence of the earlier generation of U.S. nuclear technology highlights several factors—lower costs for early models, a changing regulatory environment, and the impact of local opposition—that complicate simple learning-curve analysis and also skew the distribution of costs beyond the standard risk estimates and cost contingencies traditionally used for financing large projects (*18*).

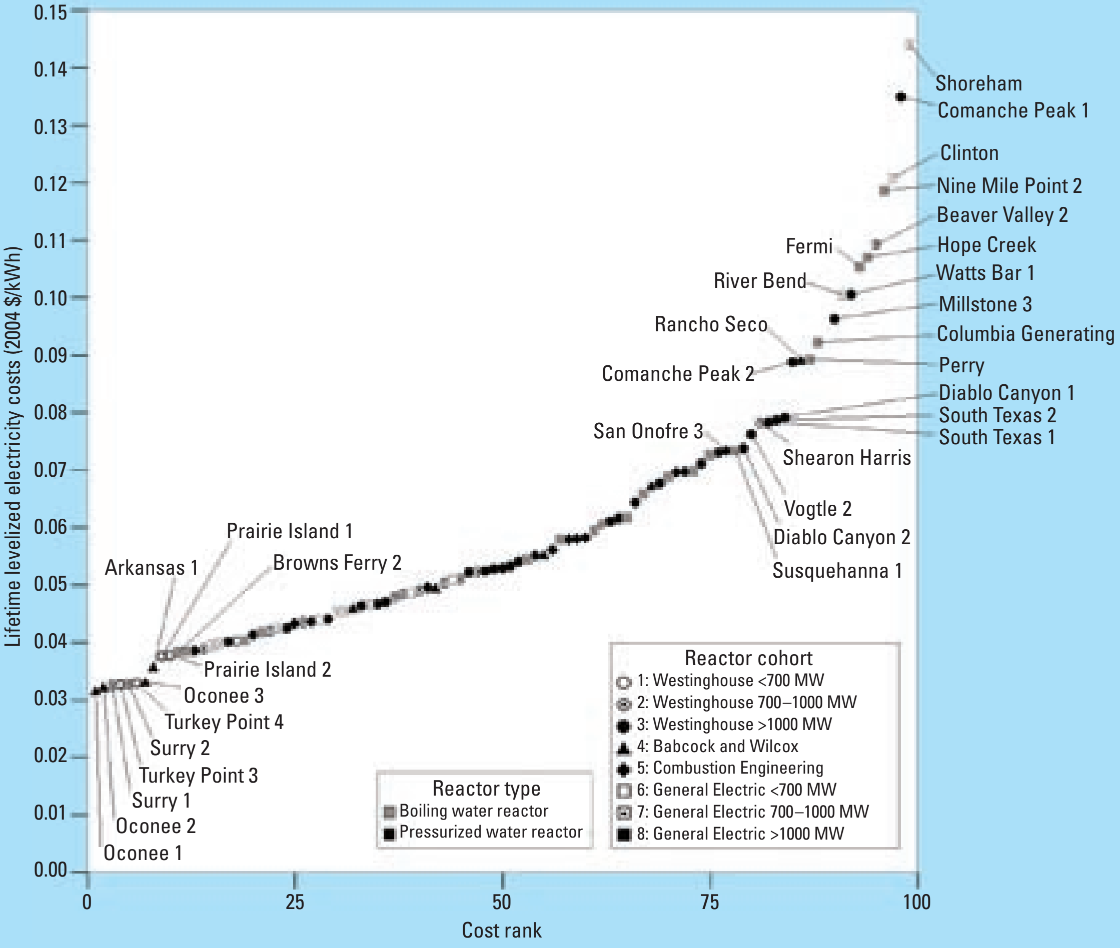
New nuclear reactors represent novel and complex technology that will retain a risk of high costs. A critical planning question, then, is how to model or account for this risk. One factor that will likely remain unchanged for the next generation is the reliance on large-scale site-built technology constructed within a rapidly changing technology and market environment, subject to local variability in supplies, labor, technology, and public opinion, all of which add uncertainty to total costs. Deregulated markets impel management to choose between investing in higher-risk, larger-scale, and more capital-intensive projects such as nuclear, and investing in established technologies, such as gas turbines, cogeneration, wind, and coal, which can generally be built more quickly than reactors. The Gen-IV project also envisions six different reactor designs, which may reduce the benefits of standardization. Despite these considerable cost risks, policy arguments continue to focus narrowly on technical possibilities for standardization, new technologies, and waste storage.

To evaluate the overall costs of existing commercial reactors, we compiled detailed data for each reactor within the entire commercial U.S. nuclear fleet and calculated a lifetime-levelized cost (in 2004 ¢/

FIGURE 1

Distribution of total levelized busbar costs for 99 U.S. reactors, including capital and operating costs

Sixteen reactors in the top quartile account for a disproportionate share of the fleet's total costs, higher than either a normal or lognormal distribution would predict. PWR = pressurized water reactor, BWR = boiling water reactor. Cohort indicates one of eight predictive cost categories described by Rothwell (*48*). Levelized costs (which exclude subsidies and externalities) are calculated using a real discount rate of 6%, as described in supporting information. Shoreham and TMI Unit 2 levelized costs are calculated assuming they operated as average nuclear reactors over a 40-year lifetime.



kWh) for each reactor (details of this analysis are available in the supporting information online). The project costing methodology used in this study is a version of the levelized present worth of revenue requirements method (*19*, *20*), which has been widely used in power project planning for many decades and is also the framework in which current U.S. nuclear plants were originally evaluated. Data were drawn from a variety of publicly available sources, and when we needed to make assumptions about future operations, we based those assumptions on recent performance. The Fort St. Vrain gas-cooled reactor, which never operated well, was omitted from this analysis because of its radically different design; however, it does bolster the points we make in this paper. The Shoreham and Three Mile Island (TMI) Unit 2 reactors present two special cases: both were shut down prematurely, the first because of a political decision and the second because of the TMI accident in 1979. For comparison with the rest of the fleet, we assumed that these reactors would have a 40-year lifetime, and we used the national averages for all cost components and operational aspects of these reactors other than capital costs.

A comparison of the lifetime levelized costs of electricity from U.S. nuclear reactors (Figure 1) exhibits a noteworthy—but, in hindsight, unsurprising—distribution that includes not only a large group of relatively low-cost reactors (e.g., with busbar [delivered] costs of 3–8 ¢/kWh, in 2004 dollars) but also a significant group of plants that raise the question of cost risks. In fact, a survey reveals that 16% of the reactors delivered total costs >8 ¢/kWh and 5% were >12 ¢/kWh. Importantly, whereas many estimates for the costs of new nuclear technology anticipate a normal or lognormal cost distribution, this high-cost cluster exceeds significantly the prices that traditional financial analysis would predict for new plants (*21*). Financial risk is often defined as the possibility of surprise, and the historical record of nuclear power clearly demonstrates this possibility.

Increasing costs

Nuclear power costs in the U.S. have undergone a well-chronicled trajectory of increasing capital and operating costs, followed by dramatic improvements in operational efficiency and reliability (*17, 22–25*). From the start of commercial nuclear reactor construction in the mid-1960s through the 1980s, capital costs (dollars per kilowatt of capacity) for building nuclear reactors escalated dramatically. Although unit costs for technology usually decrease with volume of production because of scale factors and technological learning (*26–28*), the case of nuclear power has been seen largely as an exception that reflects the idiosyncrasies of the regulatory environment as public opposition grew, regulations were tightened, and construction times increased (*15*, *29*, *30*).

Because of the low variable costs of nuclear power, this escalation in capital costs had a large impact on delivered electricity costs. In fact, for the 99 reactors for which capital cost data are publicly available, this factor explains 91.6% of the observed variance in total lifetime levelized costs ($p < 0.01$). Nevertheless, operational learning, perhaps spurred by improved economic incentives in the industry (*25*, *31*), has contributed to significant decreases in marginal electricity production costs. The Gen-IV process hopes to avoid cost overruns by integrating standardized reactor designs with tighter regulatory approval timelines. It remains to be seen whether this goal can be achieved without the construction of many reactors of each type.

After the accident at TMI in 1979, the industry was subjected to intense regulatory scrutiny and evaluation. As a result, the overall fleet capacity factor—the net generation for all reactors in the set divided by the maximum possible generation of all reactors in the set—dropped precipitously and reached its nadir in 1982 at 52.9%. During the period 2000–2004, the 69 reactors operational by 1982 had improved their overall capacity factor to 87.4%. This increase, attributable to improvements in utilization rates and decreases in service downtime (*32*), is equivalent to an additional 16.3 GW of generation just from those reactors existing in 1982—equivalent to the addition of ~15 new nuclear reactors. A similar calculation shows that such operational improvements, applied to all installations, not just the ones existing in 1982, added the equivalent of 25 new reactors. Moreover, capacity factors improved overall age classes, suggesting that the improvements were due primarily to operational learning rather than to technological differences.

The historical experience of nuclear power in the U.S. not only presents specific failures that might be addressed through policy but also suggests that new, complex, and culturally sensitive technologies risk surprises that skew the distribution of costs beyond what might be expected in a rational world. This risk affects the major stated goal for Gen-IV—that their financial risk is no greater than that for other technologies. Although each poorly performing Gen-III reactor has specific, idiosyncratic reasons for its inefficiencies, omitting underperforming assets from the analysis would introduce a survivorship bias: a focus on the remaining reactors might underestimate the uncertainty in developing new technologies. Judgments made on how to handle the probability of high-cost outliers exert a strong influence on the picture of total costs, according to our data on historical experience.

Extreme events

The statistical treatment of extreme values—and the inverse, the study of low-probability risks—is familiar to many disciplines, including hydrology (*33*, *34*); climatology (*35*, *36*); structural and safety engineering (*37*); risk analysis (*38*, *39*); insurance (*40*); and, more recently, financial markets (*41*, *42*) and even electricity markets (*43*). In each of these areas, infrequent but extreme events occur more often than one might expect from standard distributions and are often underrepresented in perceptions or policy. Our historical data indicate that, as in these other fields, extreme values are a nontrivial element of the nuclear cost distribution. Yet, to our knowledge, little research has been carried out on this question as it relates to nuclear power. The Gen-IV economic forecasts carefully specify rates of learning for each reactor class, ranging from a high-cost prototype through an "*n*th-of-a-kind" installation that represents the point at which the initial learning has already been incorporated. This method, thereby, explicitly incorporates a reasonable expectation of high-cost reactors in the early phases (*44*). Nevertheless, historical experience suggests the importance of a more thorough investigation of including cost surprise, highly skewed cost distributions, or extreme values once the reactors have been developed.

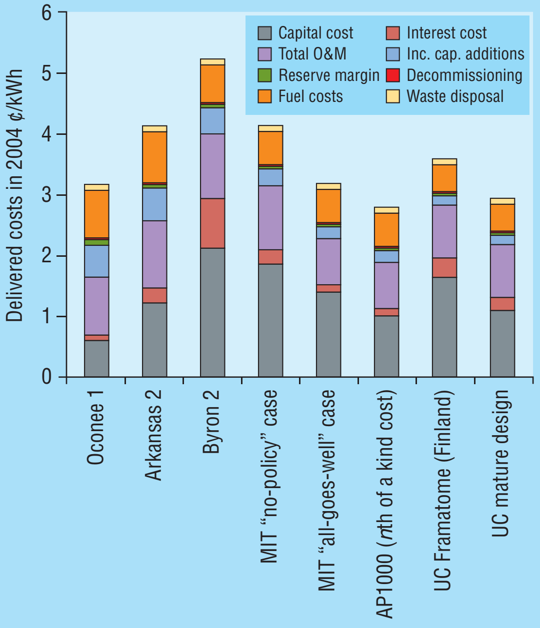
What do the historical record of costs and past successes and failures tell us? First, even though the next generation of nuclear technology and public sharing of the risks of nuclear development and deployment will mitigate costs, the costs will remain prone to what we argue are likely surprises. Expectations are high for next-generation cost reductions: the two best-performing present-day nuclear reactors (Oconee 1 and 2)—using well-tested technology run with best-industry practice—have lifetime delivered costs of ~3.2 ¢/kWh (Figure 2), which is above the projected average cost for all Gen-IV reactors when compared on a consistent basis (*9, 10*). Factors expected to lead to such cost improvements include better technology, streamlined regulation, operational incentives, design standardization, the intensive use of information technology for design, supply chain and construction management, and concern over climate change. Yet, high unit costs and long lead times lead to a slower learning rate and require more expenditures than would technologies of smaller scale, and the contextualized nature of

FIGURE 2

Consistent comparison of levelized delivered electricity costs

Three of the least expensive U.S. reactors in our sample are compared with estimates made in studies by the Massachusetts Insitute of Technology (MIT; *9*), the Generation-IV International Forum (*11*), and the University of Chicago (UC; *10*).

Discount rate is 6% real. The least costly reactor in the sample is Oconee 1; its busbar cost was 3.2 ¢/kWh. Key data (date of operation start, duration of construction, lifetime capacity factor [CF], size) for each plant are as follows: Oconee 1 (1973, 5.7 years, 77.7%, 851 MW); Arkansas 2 (1980, 7.2 years, 89.7%, 858 MW); Byron 2 (1987, 11.6 years, 93.1%, 1120 MW). The MIT construction duration is 5 years for the "no-policy" case and 4 years for the "all-goes-well" case; lifetime CF is 85%, and size is 1000 MW. Capital cost estimates for AP1000 are taken from the U.S. Department of Energy road map for 2010. Other costs and assumptions for AP1000 are assumed to be the same as for the MIT "all-goes-well" case. UC lifetime CF = 85%, size = 1000 MW, construction duration = 7 years.



site-built nuclear reactors presents a nontrivial risk of cost surprises.

Second, nuclear energy politics will clearly remain a key driver. Judging competing expectations for cost savings in the case of nuclear power requires published, comparative data to demonstrate that the lurking possibility of cost surprise will not overshadow the benefits of standardization and regulatory streamlining. A prudent and pragmatic approach would therefore engage public debate around at least the following four key recommendations.

First, conduct empirical and theoretical analyses of the role of extreme values and cost surprise in nuclear power. Our research suggests that the "fat tail" of the cost distribution has not been modeled adequately, leading to the potential for unexpectedly high-cost reactors that would affect estimates of financial risk for utilities and sponsor governments. Second, undertake comparative reviews of U.S., French, German, and Japanese cost trends (*45*), and relate these to the level of investment, regulatory involvement, and innovation that has taken place in each context.

Third, align economic incentives more closely with policy goals. The case for nuclear power resurgence rests not on expectations for dramatic growth in electricity demand but rather on concerns about energy security and climate change. Although the idea of internalizing costs for energy generation is not new, implementation of the idea lags. A carbon tax provides one approach to this problem; assessing appropriate levies on energy sources that incur security costs to society remains a policy challenge that deserves additional scrutiny.

Fourth, understand and make explicit the extent of public subsidy to nuclear power in the form of risk sharing (*46*). Currently, U.S. law insures any catastrophic losses in excess of $10.2 billion due to nuclear accidents (*47*). The economic and financial risks of nuclear incidents—at reactors, in transport, and in long-term storage—should be included in calculations comparing Gen-IV plants with other technologies, some of which enjoy other forms of public subsidy.

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Supporting information

Supporting information detailing the data, assumptions, and methods of calculation for the nuclear reactor cost results can be found online.

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