What history can teach us about the future costs of U.S. nuclear power

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Summary

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

Main Text:

One hundred 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 based on its potential to address energy security without emitting carbon dioxide 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 efficiency and distributed generation technologies (*7*). What is universally agreed 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 thoughtful integration of this discourse into eventual policy choices (*8*).

For nuclear power to play a significant role in addressing future energy needs, countries would need not only to build new reactors to replace those ending their service life, but also to expand significantly the number of commercial reactors in service. Our sixty-year experience with nuclear energy has underscored that future policy formulation requires not only an estimate of future nuclear costs, benefits, and risks, but also a 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 needs to delve deeper into whether next generation reactors might experience similar surprises.

In response to the public policy goals described earlier, a range of research and policy teams have conducted assessments of nuclear's future potential (*9,10*) and outlined plans for both incremental and fundamental changes to nuclear reactor design that are hoped will increase safety and decrease costs (*11*). The new reactors would therefore encompass evolutionary improved designs derived from the "Generation III+" machines in the near term and more radical "Generation IV" designs in the medium term. The U.S. Energy Policy Act of 2005 and the Advanced Energy Initiative (2006) seek to encourage this development by incentives for new plant construction, fast-track licensing, liability protection, and R&D 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 a number of 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 United States. 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 to other energy projects.

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*). The experience of 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 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—higher costs for early models, a changing regulatory environment, and 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 new 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 largely 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 like nuclear, or in established technologies like gas turbines, cogeneration, wind, and coal that can generally be built more quickly than reactors can. 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 ¢/kWh) for each reactor (details of this analysis are available in the online Supporting Information). The project costing methodology used in this study is a version of the levelized present worth of revenue requirements (PWRR) 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 needing 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; including it would nevertheless bolster the points we make in this paper. Shoreham and Three Mile Island (TMI) Unit 2 present two special cases: both reactors were shut down prematurely, the first because of a political decision and the second because of the Three Mile Island accident in 1979. For comparison with the rest of the fleet, we assumed that these reactors would live out a 40-year lifetime, and used the national averages for all cost components and operational aspects of these reactors other than capital costs.

Comparison of the lifetime levelized costs of electricity from U.S. nuclear reactors exhibits a noteworthy—but in hindsight unsurprising— distribution including not only a large group of relatively low-cost reactors (e.g. with busbar costs of \$0.03–\$0.08 per kWh, in 2004 dollars), but also of a significant group of plants that raise the question of cost risks. In fact, 16% of the reactors surveyed delivered total costs above $0.08 per kWh and 5% were above $0.12/kWh. Importantly, while many estimates for the costs of new nuclear technology anticipate a normally or log-normally distributed cost distribution, this high-cost cluster exceeds significantly the prices for new plants that traditional financial analysis would predict (*21*). Financial risk is often defined as the possibility of surprise, and historical record of nuclear power clearly demonstrates this possibility.

Nuclear power costs in the United States have undergone a well-chronicled trajectory of increasing capital costs and operating costs, followed by dramatic improvements in operational efficiency and reliability (*17,22-25*). From the start of commercial nuclear reactor construction in mid-1960s through the 1980s, capital costs (dollars per kilowatt of capacity) for building nuclear reactors escalated dramatically. While unit costs for technology usually decrease with volume of production due to scale factors and technological learning (*26-28*), the case of nuclear has been seen largely as an exception that reflects 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 if this goal can be achieved without constructing many reactors of each type.

After the accident at Three Mile Island (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 approximately 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 over all 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. presents not only 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 a major stated goal for Generation IV that their financial risk be no greater than that for other technologies. While each poorly performing Gen-III reactor has specific, idiosyncratic reasons for its performance, to omit underperforming assets from the analysis introduces 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, according to our data on historical experience, exert a strong influence on the picture of total costs.

The statistical treatment of extreme values—and its inverse, the study of low-probability risks—are 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 non-trivial 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 Generation-IV economic forecasts carefully specify rates of learning for each reactor class, ranging from a high-cost prototype through an "nth-of-a-kind" installation which 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 does 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 & 2)—using well-tested technology run with best industry practice—have lifetime delivered costs around 3.2 cents per kWh

(Figure 2), which is above the projected average cost for all Generation-IV reactors when compared on a consistent basis (*9,10*). Factors expected to lead to such cost improvements include improved 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 site-built nuclear reactors presents a non-trivial risk of cost surprises.

Second, it is clear that nuclear politics will remain a key driver. Judging between 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 four key components:

- Conduct empirical and theoretical analysis 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.
- 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
- Align economic incentives more closely with policy goals. The case for nuclear resurgence rests not on expectations for dramatic growth in electricity demand, but rather on concerns about energy security and climate change. While 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.

- 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 against other technologies, some of which enjoy other forms of public subsidy.

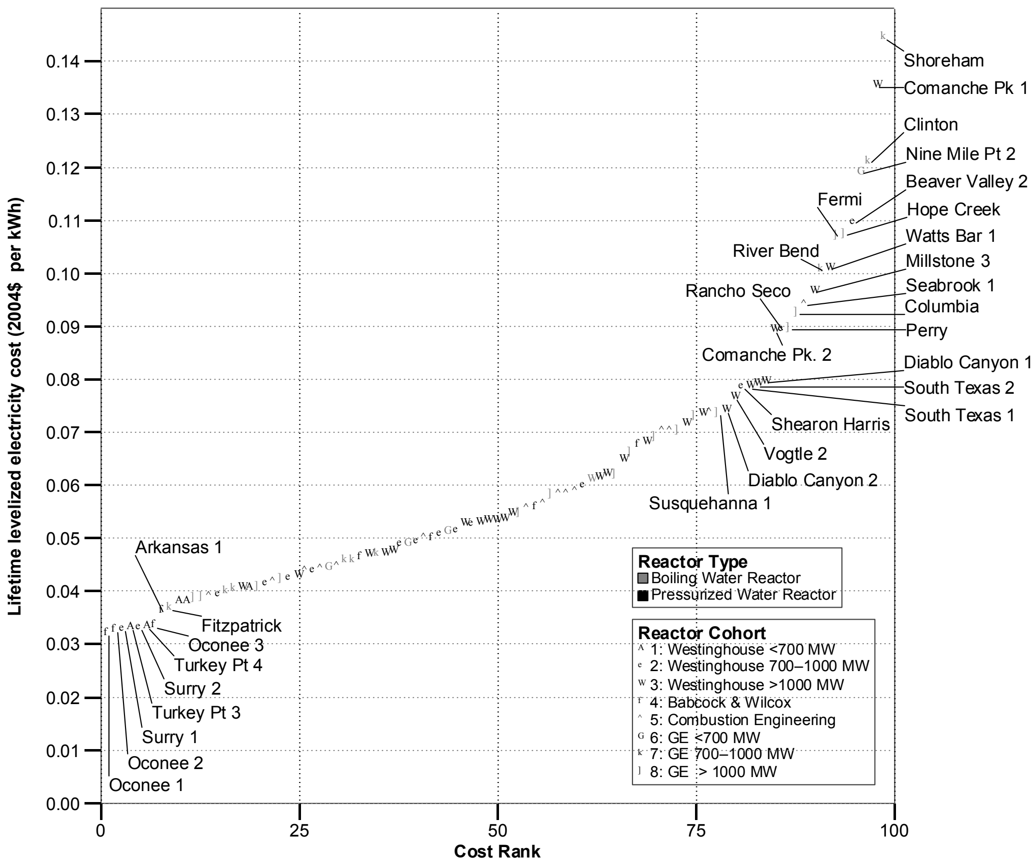

Figure 1. Distribution of total levelized busbar costs for 99 U.S. reactors, including capital and operating costs. Sixteen reactors in the top quartile account for a disproportionate share of the fleet's total costs, higher than either a normal or lognormal distribution would predict. PWR=Pressurized 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 online supplemental material. Shoreham and TMI Unit 2 levelized costs calculated assuming they operated as average nuclear reactors over a 40-year lifetime.

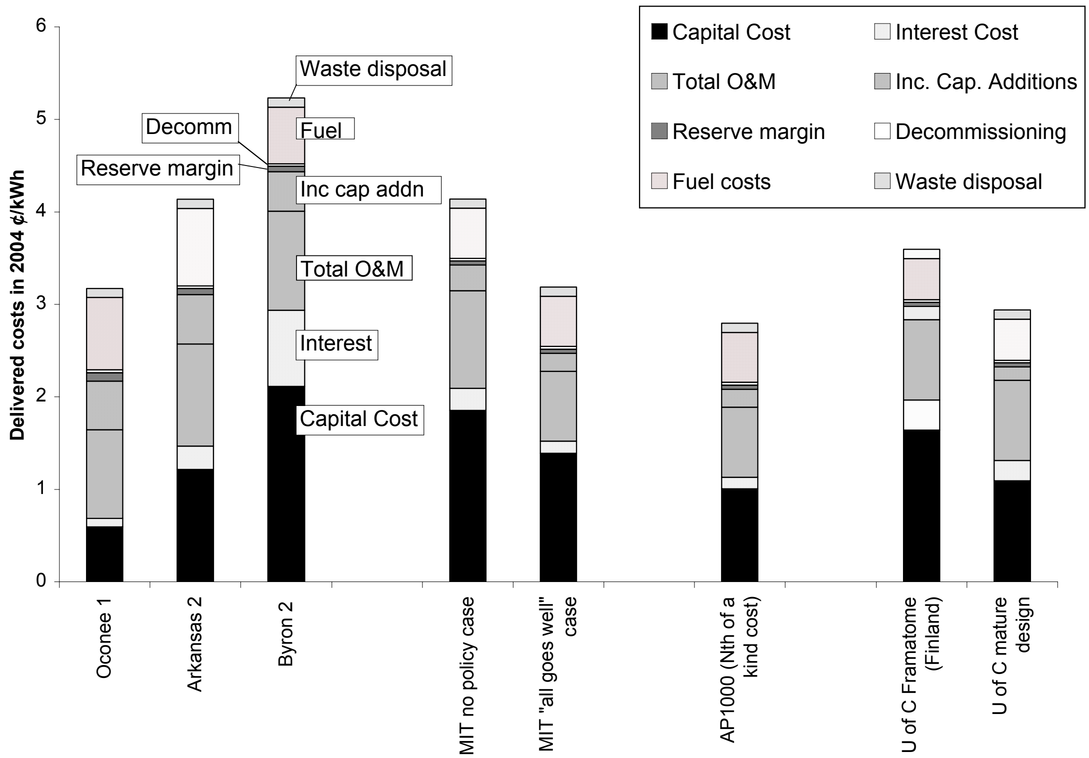

Figure 2. Consistent comparison of levelized delivered electricity costs for three of the cheapest U.S. reactors in our sample with estimates made in studies by MIT (*9*), the Generation-IV International Forum (*11*), and the University of Chicago (*10*). Discount rate is 6% real. The least costly reactor in the sample is Oconee 1, whose busbar cost was 3.2 cents/kWh. Key data for each plant are as follows. Oconee 1: Op. start 1973, Const. Duration = 5.7 years, Lifetime CF = 77.7%, size = 851 MW. Arkansas 2: Op. start 1980, Const. Duration = 7.2 years, Lifetime CF = 89.7%, size = 858 MW. Byron 2: Op. start 1987 Const. Duration =11.6 years, Lifetime CF = 93.1%, size = 1120 MW. MIT Lifetime CF = 85%, size = 1000 MW, Construction Duration = 5 and 4 years for the "no policy" and "all goes well" cases, respectively. Capital cost estimate for AP1000 taken from the U.S. DOE roadmap for 2010. Other costs and assumptions for AP1000 assumed to be the same as for the MIT "all goes well" case. U of C lifetime CF = 85%, size = 1000 MW, Construction Duration = 7 years.

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

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