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Prospects for U.S. Nuclear Power After Fukushima

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Abstract

The prospects for a revival of U.S. nuclear power were dim even before the tragic events at the Fukushima nuclear plant. Nuclear power has long been controversial because of concerns about nuclear accidents, proliferation risk, and the storage of spent fuel. These concerns are real and important. In the end, however, the key challenge for U.S. nuclear power is the high cost of construction for nuclear reactors. This article reviews the historical record of reactor orders and construction costs in the United States, highlighting some of the insights from the cancellations and cost overruns that have characterized the industry.

Introduction

In March 2011 an earthquake and tsunami knocked out power at the Fukushima Daiichi Nuclear Plant in northern Japan, causing partial meltdowns at the plant's three active reactors and large-scale releases of radioactive steam. The most significant nuclear accident since Chernobyl in 1986, the crisis has further dampened the already dim prospects for a revival of U.S. nuclear power. Of 17 applications currently pending with the Nuclear Regulatory Commission (NRC) for new nuclear power plants to be built in the United States it is unlikely that more than a few will ever be built.

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The Fukushima crisis has put an end to a recent surge in enthusiasm for nuclear power. During 2007 and 2008 the NRC received 16 license applications for a total of 24 new nuclear power reactors.[1] These applications were significant because they marked the first new license applications in the United States in almost three decades. The time was right, so it seemed, for a nuclear renaissance. Natural gas prices were at their highest level ever in real terms, the 2005 Energy Policy Act provided generous production tax credits and other subsidies for new nuclear plants, and perhaps most importantly, many believed that the United States was close to enacting legislation that would limit emissions of carbon dioxide.

Then even before Fukushima the market conditions changed abruptly. U.S. natural gas prices fell sharply in 2009, carbon legislation stalled in the Senate, and the global recession slowed the growth of electricity demand. A single additional license application was filed with the NRC in 2009 and no additional applications have been filed since. As of April 2011, most of the pending license applications are essentially stalled and pre-construction is proceeding only on a couple of projects where the regulatory environment is particularly favorable.

This ebb and flow in the nuclear power sector recalls an even larger boom and bust that occurred starting in the 1960s and the early 1970s and highlights the extreme sensitivity of the nuclear power sector to energy prices, economic downturns, national energy policy, and galvanizing events like Three Mile Island, Chernobyl, and Fukushima. Nuclear power has long been controversial because of concerns about nuclear accidents, proliferation risk, and the storage of spent fuel. These concerns are real and important. In the end, however, the key challenge for nuclear power is the high cost of construction for nuclear reactors. Several recent studies estimate that current construction costs (excluding financing) for a U.S. nuclear power reactor exceed $4000 per kilowatt, so a typical two-reactor 2000 megawatt plant would cost more than $8 billion. Following Fukushima, industry observers have called for expanded regulatory oversight for current and future nuclear power plants particularly with regard to seismic risks, containment issues and the storage of spent fuel. This increased regulatory scrutiny will likely cause construction costs to increase further.

This article examines the economics of nuclear power in the United States. I begin by reviewing

[1] U.S. Nuclear Regulatory Commission (2010), Table 9.

the historical record of reactor orders and construction costs. A number of studies have examined the cancellations and cost overruns that have characterized the industry and I summarize the most important insights. I then consider what it would take for nuclear power to become competitive, examining recent estimates of construction costs and evaluating long-standing claims that learning-by-doing and standardization will lead construction costs to decrease over time.

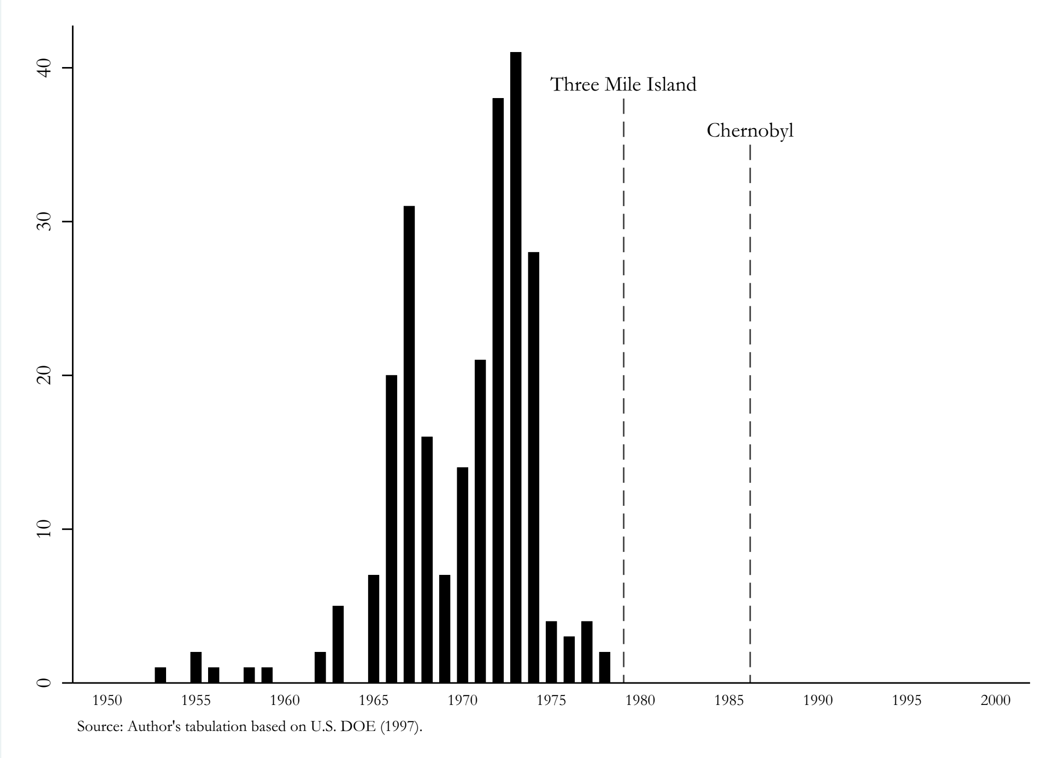
U.S. Nuclear Reactor Orders

Figure 1 plots U.S. nuclear power reactor orders from 1950 to 2000. The late 1960s and early 1970s was a period of great enthusiasm for nuclear power. Much like what happened with natural gas prices in 2007 and 2008, prices for coal and oil (the key substitute fuels of the time) were at close to historic highs and utilities were forecasting robust growth in electricity demand into the distant future.[2] By 1974 there were 54 operating nuclear reactors in the United States with another 197 on order. Seeing this surge in orders the U.S. Atomic Energy Commission (1974) predicted that by the end of the century half of all U.S. electricity generation would come from nuclear power.

Instead, reactor orders fell precipitously after 1974. Not only were reactors not being ordered, but utilities began suspending construction on existing orders. Less than half of the reactors on order in 1974 were ever completed. Much has been written about the problems that faced the nuclear industry during this period (see, e.g., Joskow and Yellin 1980, Joskow 1982, McCallion 1995). Part of the explanation is that concerns about safety and the environment began to take on a more central role. The Nuclear Regulatory Commission was created in 1974 and charged with overseeing the safety and security of all aspects of nuclear power from the initial licensing of reactors, to the handling of radioactive materials, to the storage and disposal of spent fuels. Safety codes and inspection requirements were implemented and updated, leading in some cases to extensive reactor redesigns (Cox and Gilbert 1991, McCallion 1995). During the 1970s it also became much more difficult to site nuclear power plants. Communities became more active, challenging projects

[2]For historic fuel prices see U.S. Department of Energy (2010c), Table 7.8 "Coal Prices, 1949-2009" and Table 5.18 "Crude Oil Domestic First Purchase Prices, 1949-2009". Natural gas was much less important during the 1970s both because combined cycle technologies had not yet been widely introduced and because shortages associated with federal price controls on natural gas limited the availability of natural gas for electric generation.

Figure 1: U.S. Nuclear Power Reactor Orders 1950-2000



in federal and state courts leading to extended construction delays and changing public attitudes about nuclear power.

This was also a period of structural change for utility regulation. During the 1950s and 1960s economies of scale, decreasing commodity costs, and relatively low inflation led to steady decreases in the nominal cost of electricity. Rate reviews became infrequent as utility commissions and consumers were pacified with utility prices that remained essentially the same in nominal terms year after year. Joskow (1974) explains that inflation in the early 1970s, "wreaked havoc on this process that appeared to function so smoothly before... and most major firms found that they had to raise prices (some for the first time in 25 years) and trigger formal regulatory reviews." Utility commissions and consumers were surprised and unprepared by the idea that electricity prices might actually increase and they began looking around for an explanation. Nuclear plants, because of their high cost of construction, quickly became a major focus of attention.

Then in March 1979 one of the reactors at the Three Mile Island plant in Pennsylvania suffered a partial core meltdown. Although not a single person was injured, the accident intensified public concerns about nuclear safety and further dampened enthusiasm for an industry that was already facing major challenges. The combination of severe public concern about the risk of nuclear accidents and escalating construction costs put nuclear projects in an extremely vulnerable position. By the time the Chernobyl disaster occurred in April 1986 the industry was already moribund. Today in the United States there are a total of 104 nuclear power reactors at 65 sites, accounting for 20% of U.S. electricity production.[3] All of these reactors were ordered prior to 1974.

Historical Construction Costs in the United States

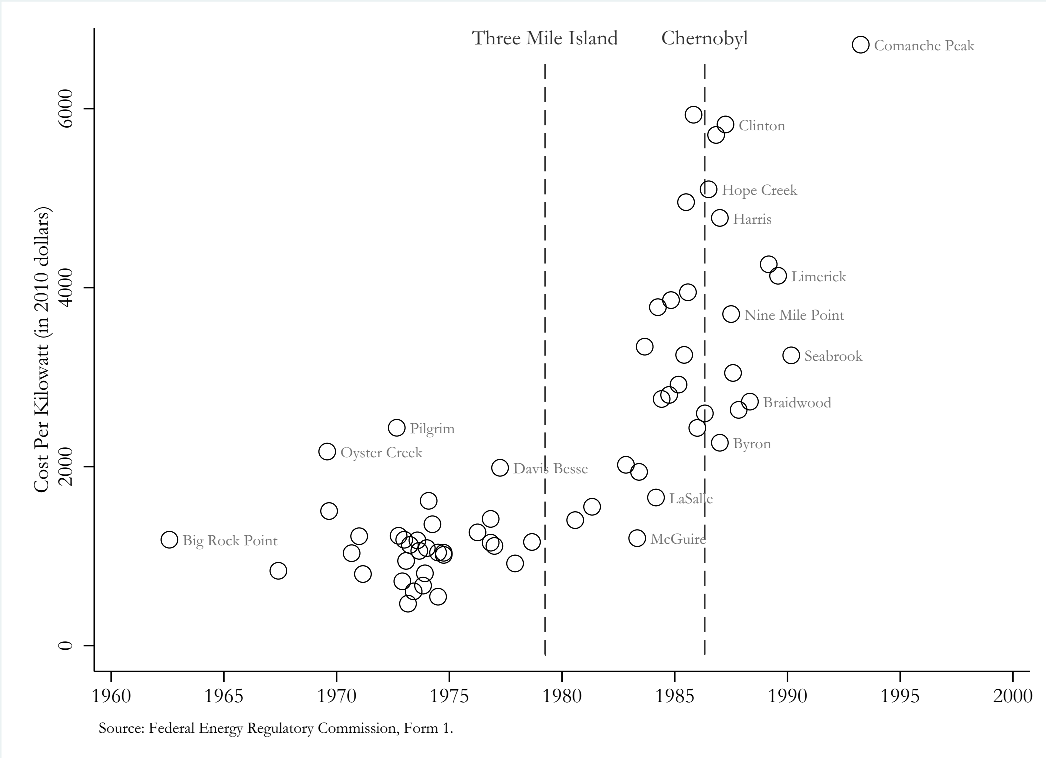
Almost every nuclear plant ever built in the United States has ended up costing more to build than was originally estimated (Zimmerman, 1982). Engineering estimates, particularly during the 1960s and early 1970s were based on "scaling up" actual costs from much smaller experimental reactors. This approach worked poorly in practice. The sheer scale of commercial-sized nuclear reactors means that most components must be specially designed and constructed, often with few potential suppliers worldwide. These components are then assembled on site and structures are constructed to house the assembled components. All stages of design, construction, assembly, and testing require highly-skilled, highly-specialized engineers and differences in reactor design and site-specific factors have historically meant that there was little scope for spreading design and production costs across multiple projects (Komanoff, 1981).

Figure 2 plots construction costs including financing charges for U.S. nuclear power plants completed in the United States between 1960 and 2000. Costs are reported in year 2010 dollars per kilowatt of capacity. The figure reveals a pronounced increase in construction costs beginning with plants completed during the 1980s. Most plants completed after the Three Mile Island accident in 1979 cost more than $2500 per kilowatt to build. This increase in construction costs has been widely studied but is still not completely understood.[4]

[3]U.S. Department of Energy (2010), Table 8.2a Electricity Net Generation. Other sources include coal (45%), natural gas (23%), hydroelectric power (7%), wind (2%), other forms of renewable energy (2%) and oil (1%). Davis and Wolfram (2011) examine in detail current performance at U.S. nuclear plants.

[4]See, for example, Mooz (1978), Komanoff (1981), Zimmerman (1982), U.S. Department of Energy (1986), and Koomey and Hultman (2007). In related work Joskow and Rose (1985) examine increases in construction costs for

Figure 2: Construction Costs for U.S. Nuclear Power Plants Completed 1960-2000



Part of the explanation for the increase in cost is that plants kept taking longer and longer to build. Table 1 describes U.S. nuclear reactor orders and construction times by decade. Construction times increase steadily across decades. Of 155 reactors ordered during the 1970s, only 25% were eventually completed and those reactors took an average of 14 years to finish. Most studies attribute this increase in construction time to a rapidly evolving regulatory process. A joke in the industry was that a reactor vessel could not be shipped until the total weight of all required paperwork had equaled the weight of the reactor vessel itself. The NRC has recently adopted several new procedures intended to streamline the regulatory process. These reforms include pre-approving standard reactor designs, an early site permitting process, and combining construction and operating licenses which previously were applied for separately. These new procedures have not yet been fully tested so it remains to be seen how well they will work in practice.

coal-burning plants during the same period.

Table 1: U.S. Nuclear Reactor Orders and Construction Time By Decade

			Construction Time (in Years) For Completed Reactors		
Decade	Number of Reactors Ordered	Percent Eventually Completed	Average	Minimum	Maximum
1950s	6	100%	4.5	3	7
1960s	88	89%	8.6	3	22
1970s	155	25%	14.1	8	26

Source: Author's tabulations based on U.S. Department of Energy (1997). Construction time is calculated as the difference in years between when a reactor is ordered and when it begins commercial operation.

The Cost of Capital and Cancellation Risk

This long period of time required for construction means that the cost of capital is a critical parameter for evaluating the viability of nuclear power. Table 2 provides a hypothetical example that illustrates how financing costs during construction can represent a substantial fraction of total construction costs. Several scenarios are considered ranging from a real cost of capital of 5% to 15% and a construction period of 1 to 10 years. For each scenario the table reports financing costs during construction as a fraction of total construction costs. For these calculations I assume that expenditures are uniformly distributed across months during the construction period and that financing charges accrue monthly at the cost of capital. With a cost of capital of 10% and a five-year construction period, financing costs are 22% of total construction costs. With the same cost of capital and a ten-year construction period, financing costs are 40% of total construction costs.

Table 2: An Illustration of Why Financing Costs Matter

Financing Costs as a Fraction of Total Construction Costs

	Construction Period		
	One Year	Five Years	Ten Years
5% Cost of Capital	2%	12%	22%
10% Cost of Capital	4%	22%	40%
15% Cost of Capital	6%	30%	54%

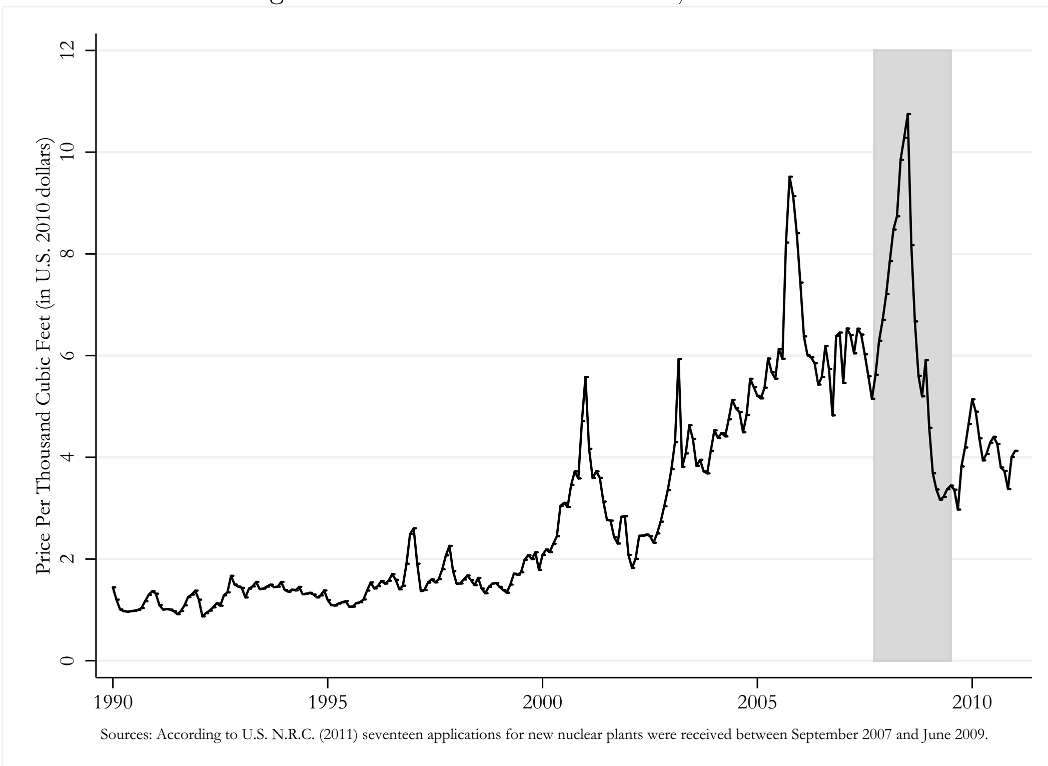
Even for a low cost of capital, an extended construction period imposes financing costs that are a substantial part of total project costs. However, nuclear projects typically face a cost of capital well above the risk-free rate. These are large-scale projects with a historically high risk of default and the high cost of capital reflects the fact that there are a number of sources of risk that threaten the profitability, and even viability, of a nuclear project.

More so than in most other investments, potential builders of nuclear power plants face substantial regulatory risk. Regulatory approval is required at the federal, state, and local level and there is precedent for this being a real constraint on plants. For example, in 1989 New York Governor Mario Cuomo and the Long Island Lighting Company closed the Shoreham Nuclear Power Plant over long-standing concerns about how nearby residents would be evacuated in the event of an emergency. The plant was 100% completed and had been connected to the grid, yet was never used to produce a single kilowatt of commercial electricity (McCallion 1995). Anticipating siting challenges the applications currently pending with the NRC are mostly for reactors that would be built at existing nuclear sites rather than plants in new locations.

Nuclear power is also sensitive to federal energy policy. The enthusiasm for nuclear power in 2007 and 2008 was driven in part by the prospect of a federal cap on carbon emissions and when H.R. 2454 (the "Waxman Markey bill") stalled in the Senate in 2009 this was viewed as a significant blow to the economic viability of new nuclear plants. More recently the Obama administration and some members of Congress have voiced support for a federal "clean energy standard" under which a proportion of total electricity generation would be required to come from sources other than coal. Such a policy could be a considerable boost for nuclear power, but the exact form of such legislation or the likelihood with which it would be adopted are still unclear.

In addition to these regulatory risks, investors in nuclear power also face numerous forms of market risk. Perhaps most importantly, nuclear plants face the risk that fossil fuel prices will decrease. In the United States natural gas prices typically determine the marginal cost of electricity, so a decrease in natural gas prices reduces profits for nuclear power plants who sell power in wholesale electricity markets. Figure 3 plots average monthly U.S. natural gas wellhead prices during 1990-2010. The shaded area indicates the time period between September 2007 and June 2009 during which the NRC received applications for new nuclear plants. It is no coincidence that during the long period of relatively low natural gas prices there was little activity in nuclear power.

Figure 3: U.S. Natural Gas Prices, 1990-2010



The surge of nuclear orders during 2007 and 2008 corresponds to the highest U.S. natural gas levels ever in real terms, and only one order has been received since prices fell in 2009. The U.S. Department of Energy (2011a) predicts that average natural gas prices in the United States will remain under $5 through 2022 which, if true, represents a significant challenge for nuclear power.

Finally, investments in nuclear power face considerable technology risk. Over the 40+ year lifetime of a nuclear power reactor the available sources of electricity generation could change and there is risk that an alternative, lower-cost technology could come along. This could be a technology that is known today such as wind or solar that quickly becomes more cost-effective or some other technology that is currently unknown. Alternative forms of carbon abatement represent another form of technology risk, including, for example, carbon capture and storage or energy efficiency technologies that reduce electricity demand.

These different forms of risk mean that the cost of capital for nuclear projects is well above the risk-free rate. So who is currently investing in nuclear power? Probably farthest along are plans by the Southern Company and South Carolina Electric and Gas to build new reactors in Georgia and South Carolina. Both companies are subject to traditional rate-of-return regulation so ratepayers bear much of the risk of these projects. This was the typical case during the first wave of U.S. nuclear power plant construction, with cost overruns borne primarily by ratepayers rather than shareholders.[5]

Current Estimates of Construction Costs

Historic construction costs are an important starting point and the closest available empirical estimates for the cost of building a nuclear power plant in the United States. Particularly given the poor track record in the industry at predicting costs, there is a strong argument for making decisions based on actual cost realizations rather than engineering estimates. That being said, one should not lose sight of the fact that these historical data come from plants that were completed many years ago and for which construction began in the 1970s. With no recent U.S. experience to point to there is a great deal of uncertainty about current construction costs. Nonetheless, several studies have attempted to synthesize the available historical information with engineering estimates, input prices, and more recent information about construction costs from plants outside of the United States to put a point estimate on current construction costs.

Table 3: Construction Costs for the United States Excluding Financing

	Costs Per Kilowatt (in year 2010 dollars)		
Source	Nuclear	Coal	Natural Gas
MIT (2009)	4200	2400	900
U.S. DOE (2010b)	5300	2800	1000

Table 3 reports estimates of "overnight" construction cost in year 2010 dollars from two recent

[5]Joskow (2006) discusses the evolving regulatory environment and how it impacts investment in new nuclear plants. In related work, Zimmerman (1988) points out that cancellations of partially completed plants typically received far less generous regulatory treatment than completed plants. This asymmetric treatment of sunk costs leads to divergent incentives for utilities and consumers, with consumers finding it in their interest to force cancellation of socially efficient projects.

studies. The overnight cost is the hypothetical cost of a plant if it could be built instantly, and thus excludes financing and other costs incurred during plant construction. MIT (2009) estimates $4,200 per kilowatt for nuclear, compared to $2,400 and $900 per kilowatt for coal and natural gas. U.S. Department of Energy (2010b) predicts somewhat higher costs particularly for nuclear plants, citing increased prices for plant components and key commodities and arguing that costs will be driven up by the fact that there is a limited set of construction firms with the ability to complete a project of this scale. Both studies were completed prior to Fukushima and thus do not incorporate any cost increases due to recent elevated regulatory scrutiny.

Adding financing costs to these estimates moves them near the high-end of the cost range observed during the 1980s and 1990s. This is probably not unreasonable. The long period of time since nuclear power plants were constructed in the United States means that the entire supply infrastructure will need to be started up again essentially from scratch. To the extent that there was relevant experience accumulated by companies involved with nuclear engineering and plant construction, this has likely atrophied to a large degree (Joskow and Parsons, 2009). There is some scope for importing nuclear engineers and other professionals who have worked on more recent nuclear builds in other countries, but the overall level of nuclear construction activity worldwide over the last 20 years has been so low that there is a limited amount of available global talent.

Moreover, the supply of many plant components is now more limited than it was during the first wave of plant construction. For example, there is today only one facility in the world that can produce the nuclear-grade heavy-steel reactor vessel needed for a boiling water reactor and there is currently a long waiting period for these forgings and for other key nuclear components (Ives, McCabe and Gilmartin 2010). Without international standards for nuclear components there will inevitably be delays as the NRC certifies internationally-sourced components.

Evidence from nuclear reactor construction outside the United States is mixed. Du and Parsons (2009) provides a recent analysis of international construction costs. For five reactors completed in Korea and Japan between 2004 and 2006, Du and Parsons reports a mean overnight cost of $3,100 (in 2010 dollars), lower than most current estimates for the United States. In contrast, construction costs are likely to be considerably higher for two new nuclear power plants currently under construction in Europe.[6] In Olkiluoto, Finland, construction began in 2005 and was expected to finish in 2009 at a cost of about $2,800 per kilowatt. A series of problems and delays have now pushed operations back to 2013, and costs are now estimated to be about twice the original estimate. Similarly, construction of the Flamanville plant in France began in 2007 and the plant was expected to open in 2011 at a cost of $2,900 per kilowatt. The plant opening has been pushed back to 2014 and the project is reported to be 50% over budget. In both cases production was slowed substantially when federal safety inspectors found problems. In Finland, the concrete foundation of the reactor building was found to be too porous. In France, inspectors found cracks in the concrete foundation and steel reinforcements in the wrong places. Project managers have been blamed in both projects for hiring inexperienced contractors and for providing insufficient oversight. International comparisons are fraught with difficulties but this experience provides a valuable reminder about some of the problems that can occur during reactor construction.

Thus there is a great deal of uncertainty about exactly how much it would cost to build a new nuclear power plant in the United States. Some industry analysts argue that construction costs could be much lower than the estimates reported in Table 3 (Nuclear Energy Institute, 2009), while the recent evidence from Europe suggests costs could be even higher. This uncertainty about costs is itself a barrier to investment. Pindyck (1993) uses a model of irreversible investment to illustrate how uncertainty over the prices of construction inputs and over government regulation affecting construction costs can lead investors to delay investment on nuclear projects. Resolving this uncertainty about construction cost has public value and this is one of the economic arguments made in support of the production tax credits and other subsidies for new nuclear plants in the 2005 Energy Policy Act. If the industry could indeed demonstrate that a plant can be constructed at low-cost and in a reasonable time horizon this would encourage broader investment in the industry.

[6] Much has been written about these plants because they are the first new nuclear plants to be constructed in Europe in many years. See, e.g., Guy Chazan, "Jinxed Plant Slows a Nuclear Rebirth," *Wall Street Journal*, December 2, 2010 and James Kanter, "In Finland, Nuclear Renaissance Runs Into Trouble," *New York Times*, March 29, 2009.

What Would It Take For Nuclear To Be Competitive in the U.S.?

Incorporating Variable Costs and a Carbon Tax

The total cost of producing electricity depends not only on construction costs but also on operations and maintenance expenditures including fuel. These variable costs tend to be lower for nuclear than coal or natural gas, potentially offsetting the higher cost of construction. Table 4 reports levelized costs for four different scenarios. These estimates are based on a cash flow model developed in an ongoing series of studies perfomed at MIT (MIT 2003, MIT 2009, Joskow 2006, Du and Parsons 2009, and Joskow and Parsons 2009). The model performs lifetime analyses to calculate the total cost of electricity from nuclear, coal and natural gas. All costs including construction, operation, maintenance, fuel, etc are calculated and discounted back to the present using an assumed cost of capital. This total cost is then "levelized" over the lifetime of a plant in constant dollars to yield the levelized cost of producing a kilowatt hour of electricity. This is equivalent to the real price per kilowatt hour that the plant would need to receive over its lifetime in order to exactly break even.

Table 4: Levelized Costs Comparison

	Levelized Costs in Cents Per kWh			Break Even Construction Cost ($ per kilowatt)
	Nuclear	Coal	Natural Gas	
MIT (2009) Baseline	8.7	6.5	6.7	$2700
Updated Construction Costs Using U.S. DOE (2010b)	10.4	7.0	6.9	$2900
Updated Construction Costs and Fuel Prices	10.5	7.4	5.2	$1800
Carbon Tax of $25 Per Ton CO_2	10.5	9.6	6.2	$2500

Note: These calculations follow MIT (2009) except where indicated in row headings. The last column reports the nuclear construction cost (in year 2010 dollars per kilowatt capacity) below which nuclear generation becomes the low-cost technology.

Several lessons emerge from these comparisons. First, under the baseline assumptions in row (1) nuclear is not competitive with either coal or natural gas. Updated to reflect year 2010 prices, MIT (2009) reports a levelized cost for nuclear power of 8.7 cents per kilowatt hour, compared to 6.5 cents for coal, and 6.7 cents for natural gas. This gap widens in row (2) with the updated construction cost estimates from U.S. Department of Energy (2010b).

Second, the cost of capital is an extremely important parameter in these analyses. The MIT studies apply a somewhat higher cost of capital to nuclear power than to fossil-fuel based power. This higher cost of capital reflects the historically high risk of default and numerous forms of risk faced with nuclear projects. Decreasing the cost of capital reduces the levelized costs for nuclear making it more competitive with coal and natural gas. However, even without this risk premium nuclear still has the highest levelized cost. An important related factor is the construction period. We follow the MIT studies in assuming that the construction period for nuclear power plants is five years, compared to four years for coal and two years for natural gas. These assumptions are fairly generous to nuclear given the industry's history of construction delays. As illustrated earlier, increasing the construction period would have a substantial impact on total construction costs.

Third, the prospects for nuclear depend critically on fuel prices. Row (3) updates the estimates to reflect 2011 fuel prices. As of 2011, prices for uranium and coal are both up somewhat from the baseline case used in MIT (2009), but natural gas prices are substantially below the baseline ($5.15 per MMBtu compared to $7.00 per MMBtu).[7] This lower price for natural gas substantially reduces the levelized cost of natural gas and makes it difficult to make a case for nuclear power.

Fourth, a modest carbon tax improves the prospects for nuclear, but under most conditions this is not enough to make nuclear economic. Row (4) incorporates a tax of $25 per ton of carbon dioxide.[8] Under this scenario nuclear continues to have the highest levelized cost. The levelized cost of coal increases by $.02 per kWh, but the levelized cost of natural gas increases by only about $.01.[9]

[7] Updated fuel prices come from U.S. Department of Energy (2010a, 2011b, 2011c). Uranium prices end up being less important than fossil fuel prices because they represent a small proportion of the total cost of nuclear power. Even after including costs for conversion, enrichment, and fuel fabrication, nuclear fuel costs are typically less than one cent per kilowatt hour. See Du and Parsons (2009) for details. Moreover, the medium to long-run supply of uranium is highly elastic with substantial known reserves worldwide with a cost of recovery below current uranium prices (MIT 2003, Appendix 5.E; OECD 2009).

[8] As a point of comparison the Federal Interagency Working Group (2010) adopts a central social cost of carbon dioxide of $22 for 2015.

[9] Moreover, this static comparison based on current fuel prices is likely misleading because coal and natural gas prices would likely fall in response to carbon policy. For both coal and natural gas there is a range of different sources available, much of which with a marginal cost of extraction below current prices.

It is important to emphasize that these levelized cost estimates depend on a series of assumptions, many of which can be only partially verified empirically. Perhaps most importantly, alternative assumptions about nuclear construction costs or natural gas prices can begin to change the outlook considerably. Moreover, it is worth highlighting that these cost estimates are for the United States only and do not easily generalize to other countries considering investments in nuclear power. The economics of nuclear power depend on many country-specific factors including the regulatory environment and the cost of alternative energy sources. For example, in countries where natural gas is more expensive the economics of nuclear power are more favorable. Construction costs also vary substantially across countries due to differences in the cost of labor and other inputs.

Learning-By-Doing and Standardization

Some industry analysts argue that learning-by-doing will push down construction costs over time. A substantial literature in economics indicates that learning-by-doing matters in a variety of markets (Alchian 1963, Joskow and Rose 1985, Irwin and Klenow 1994, Benkard 2000, Thornton and Thompson 2001, Kellogg forthcoming). Moreover, learning-by-doing was one of the arguments made by supporters of the 2005 Energy Policy Act which provides production tax credits and other subsidies for the first six gigawatts of new nuclear plants. The Nuclear Energy Institute testified in Congress, for example, that after the first couple of plants, overnight costs would go down from $1,400 per kilowatt to approximately $1,000, after which "all future plants would be financed and built without federal government financial assistance" (Nuclear Energy Institute, 2004).

Again the historical record provides an important point of comparison. The fact that construction costs tended to increase during the 1970s and 1980s does not in itself rule out learning-by-doing, and several studies have attempted to disentangle learning-by-doing from industry-wide factors that were changing over time. Both Mooz (1978) and Komanoff (1981) find evidence of modest amounts of learning-by-doing in nuclear plant construction that accrue to the construction company in charge of the project, but no evidence of industry-wide learning-by-doing. Zimmerman (1982) also finds learning-by-doing for the construction company, and finds some evidence of industry-wide learning. McCabe (1996) again finds evidence of company-specific learning, particularly for utilities that performed the construction themselves, but does not test for industry-wide learning.

The learning-by-doing argument for an industry-specific subsidy hinges on there being learning-by-doing that is not captured by the individual companies performing the construction. If learning is fully appropriable, then firms face efficient incentives for investment and no government intervention is necessary. Moreover, while there is almost certainly some industry-wide learning in nuclear, there is likely to be even more for emerging technologies such as wind and solar. Nuclear power generation is a proven, demonstrated technology and investors are not waiting on the sidelines to see if these plants will work. When there are a number of competing alternatives most economists favor broad-based subsidies that do not single out individual technologies (Schmalensee 1980).

A related argument is the idea that increased standardization will lower costs and facilitate information spillovers across plants. The first wave of U.S. nuclear reactors were manufactured by four different companies (Westinghouse, General Electric, Combustion Engineering, and Babcock & Wilcox) with a diversity of different designs. In part these differences were inevitable. The United States led the way in the development of commercial nuclear reactors and the technology was evolving rapidly.

An interesting point of comparison is France, where development began later and with much less design variation. When Électricité de France began seriously building reactors in the 1970s it adopted a single design (the Westinghouse pressurized water reactor) for all of its reactors. With one exception, the 59 nuclear power reactors currently in operation in France all are of exactly this same design.[10] Lester and McCabe (1993) find that this uniformity has increased learning-by-doing in plant operation. In principle, standardization could also decrease construction costs and increase safety and reliability.

Many within the nuclear industry claim that the industry is headed more toward the French model. A chairman of a major nuclear power company recently reported that new reactors would be standardized down to "the carpeting and wallpaper".[11] However, this claim does not appear to be supported by the license applications that have been received to date. Among the 17 applications that have been received by the NRC, there is a mix of both pressurized water reactors and

[10] International Atomic Energy Agency (2010).

[11] Michael Wallace, Chairman of UniStar Nuclear Energy, quoted in the New York Times, May 28, 2009.

boiling water reactors, manufactured by five different reactor manufacturers (Areva, Westinghouse, Mitsubishi, GE-Hitachi, and GE). Thus, it may well be the case that the industry will soon coalesce around a very small number of designs, but this is not immediately obvious based on these initial applications. At a minimum it seems clear that the French approach of supporting a single reactor design is not going to be adopted here.

Conclusion

It is not surprising that despite the challenges nuclear power continues to generate enthusiasm. A single pound of reactor-grade uranium oxide produces as much electricity as over 16,000 pounds of coal – enough to meet the needs of the average U.S. household for more than one year.[12] Moreover, while burning this amount of coal generates thousands of pounds of carbon dioxide, sulfur dioxide, and nitrogen oxides – nuclear power is virtually emissions free.

The crisis at the Fukushima plant has brought to the forefront ongoing concerns about nuclear accidents and the handling and storage of spent nuclear fuel and reminded the world about the risks associated with nuclear power. However, in the end, the biggest stumbling block for nuclear power continues to be cost. In 1942 with a shoestring budget in an abandoned squash court at the University of Chicago, Enrico Fermi demonstrated that electricity could be generated using a self-sustaining nuclear reaction. Seventy years later the industry is still trying to demonstrate how this can be scaled up cheaply enough to compete with coal and natural gas.

The chairman of one of the largest U.S. nuclear companies recently said that his company would not break ground on a new nuclear plant in the United States until the price of natural gas was more than double today's level and carbon emissions cost $25 of ton.[13] This seems to pretty well summarize the current prospects for U.S. nuclear power. Yes, there is a confluence of factors that could make nuclear power a viable, economic option. Otherwise, it seems unlikely that there will be much of a renaissance.

[12] Author's calculations based on U.S. Department of Energy (2010c), Table 8.2a "Electricity Net Generation", Table 8.5a "Consumption of Combustible Fuels", Table 8.9 "Electricity End Use", Table 9.3 "Uranium Overview", and Table 12.7b "Emissions from Energy Consumption for Electricity Generation".

[13] John W. Rowe, the chairman of Exelon, quoted in the New York Times, November 16, 2010.

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