

Prospects for Nuclear Power

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In September 2007, the U.S. Nuclear Regulatory Commission (NRC) received a license application for a proposed nuclear power reactor to be built in southern Texas. The application marked the first new license application in almost three decades. During the following year, the NRC received 16 license applications for a total of 24 proposed reactors. The time was right, so it seemed, for a nuclear power renaissance in the United States. Natural gas prices were at their highest level ever in real terms. The 2005 Energy Policy Act provided loan guarantees, production tax credits, and other subsidies for new nuclear plants. Many believed that the United States was close to enacting legislation that would limit emissions of carbon dioxide.

Then everything changed. Natural gas prices fell sharply in 2009. Legislation to limit carbon emissions stalled in Congress. The global recession slowed the growth of electricity demand. And 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. Since 2009, only a single additional license application has been filed with the NRC. The project proposed for southern Texas has been canceled, and few of the applications pending with the NRC are moving forward. Fukushima has had perhaps an even stronger impact worldwide, leading Germany, Switzerland, and Italy to announce plans to phase out their nuclear power programs and causing China to suspend approvals for new reactors.

Nuclear power has long been controversial because of concerns about nuclear accidents, storage of spent fuel, and about how the spread of nuclear power might

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doi=10.1257/jep.26.1.49

raise risks of the proliferation of nuclear weapons. These concerns are real and important. However, emphasizing these concerns implicitly suggests that unless these issues are taken into account, nuclear power would otherwise be cost effective compared to other forms of electricity generation. This implication is unwarranted. Throughout the history of nuclear power, a key challenge has been the high cost of construction for nuclear plants. Construction costs are high enough that it becomes difficult to make an economic argument for nuclear even before incorporating these external factors. This is particularly true in countries like the United States where recent technological advances have dramatically increased the availability of 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 until the price of natural gas was more than double today's level and carbon emissions cost \$25 per ton (Wald 2010). This comment summarizes the current economics of nuclear power pretty well. Yes, there is a certain confluence of factors that could make nuclear power a viable economic option. Otherwise, a nuclear power renaissance seems unlikely.

The First Boom and Bust

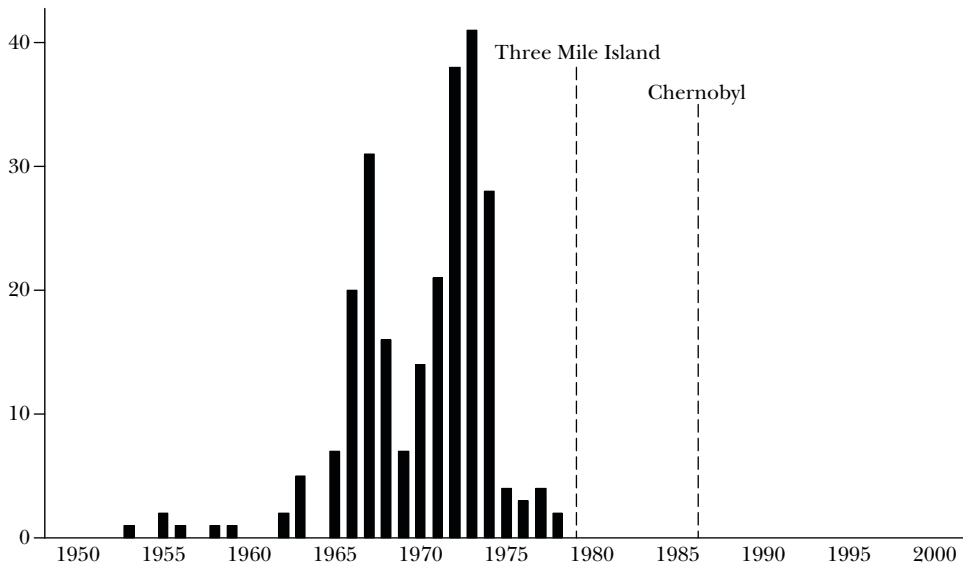
This recent ebb and flow in the nuclear power sector recalls a much larger boom and bust that occurred starting in the 1960s and 1970s. Figure 1 plots U.S. nuclear power reactor orders from 1950 to 2000. By 1974, there were 54 operating reactors in the United States with another 197 on order. This period was one of great enthusiasm for nuclear power. U.S. coal prices were at their highest level ever in real terms, and utilities were forecasting robust growth in electricity demand into the distant future.¹ The U.S. Atomic Energy Commission (1974) predicted that by the end of the twentieth century half of all U.S. electricity generation would come from nuclear power.

Instead, reactor orders fell precipitously after 1974. Over the next several years not only were new 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 (for example, Joskow and Yellin 1980; Joskow 1982; McCallion 1995). Part of the explanation is that concerns about safety and the environment began to take a more central role. In 1974, the Nuclear Regulatory Commission was created to replace the Atomic Energy Commission, which had previously been charged with both regulating and promoting nuclear

¹ For historic coal prices, see U.S. Department of Energy (2011a, table 7.9 "Coal Prices, 1949–2010"). Natural gas was much less important during the 1970s because modern combined cycle technology 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



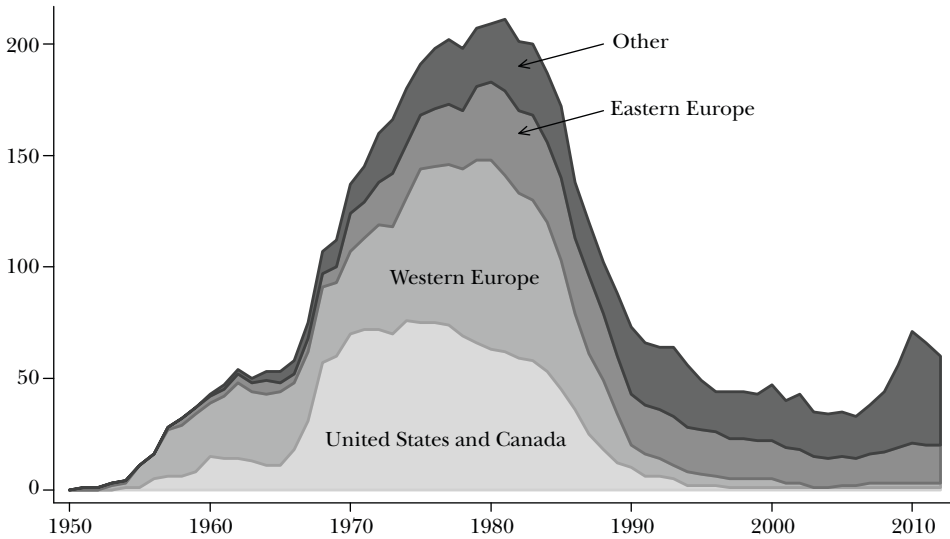
Source: Author based on data from U.S. Department of Energy (1997).

power—a combination of duties which many viewed to be in direct conflict. This new organization was to oversee the safety and security of all aspects of nuclear power, including the initial licensing of reactors, the handling of radioactive materials, and the storage and disposal of spent fuels. Beginning in the 1970s, it also became more difficult to site nuclear power plants. Communities began challenging nuclear power projects in federal and state courts, leading to extended construction delays and changing public attitudes about nuclear power.

Utility regulation also experienced structural change at this time. 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. Public utility commissions and consumers were pacified with 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.” These reviews led to increased scrutiny of utilities’ capital expenditures, and in particular, investments in nuclear plants.

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. The combination of severe public concern about the risk of nuclear accidents and

Figure 2

Nuclear Reactors under Construction Worldwide

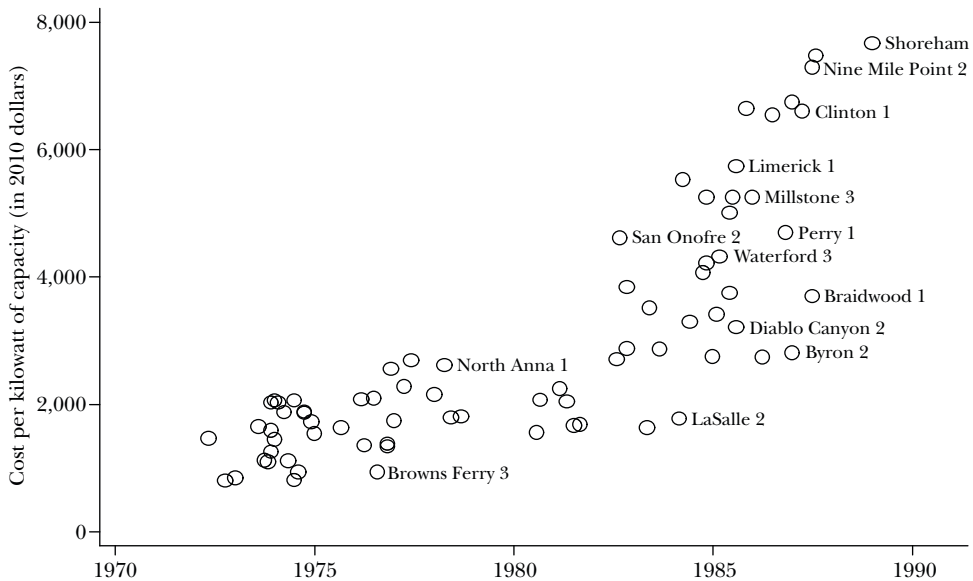
Source: Author based on data from International Atomic Energy Agency (2011).

escalating construction costs put nuclear projects in an extremely vulnerable position. By the time the Chernobyl disaster occurred in April 1986, expansion of U.S. nuclear power had largely halted. Today in the United States, there are a total of 104 nuclear power reactors at 65 sites, accounting for 20 percent of U.S. electricity generation (U.S. Department of Energy 2011a, table 8.2a).² All of these reactors were ordered prior to 1974.

Nuclear reactor construction outside the United States followed a similar pattern with a substantial boom in the 1960s and 1970s, followed by a long period of decline, shown in Figure 2. In addition to the United States, the other large-scale early adopters of nuclear power were the United Kingdom, France, Germany, Canada, and Japan. By the 1990s, construction had moved to Eastern Europe and in particular Russia and the Ukraine. The increase in construction 2008–2010 comes primarily from China, which today has more reactors under construction than any other country.

² U.S. Department of Energy (2011a, table 8.2a) also reports that U.S. net generation of electricity in 2010 includes coal (45 percent), natural gas (24 percent), nuclear (20 percent), hydroelectric power (7 percent), and wind and other renewables (4 percent). In Davis and Wolfram (2011), my coauthor and I examine in detail operating performance at U.S. nuclear plants.

Figure 3

Construction Costs for U.S. Nuclear Reactors by Year of Completion

Source: U.S. DOE (1986), table 4.

Notes: Figure 3 plots “overnight” construction costs for selected U.S. nuclear power plants from the U.S. Department of Energy (1986). The figure includes *predicted* costs from the same source for a handful of reactors that were under construction but not yet in operation in 1986.

Historical Construction Costs

Nuclear power plants are characterized by high construction costs and relatively low operating costs. Later in the paper, I present estimates of “levelized costs,” which facilitate comparisons with other generating technologies with different cost profiles over time. It is worth starting with construction costs, however, because they represent a large share of the total cost of nuclear power.

Nuclear power plants are enormous facilities with high construction costs. 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. 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.

Figure 3 plots “overnight” construction costs for selected U.S. nuclear reactors from the U.S. Department of Energy (1986). 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. Costs are reported in year 2010 dollars

Table 1
U.S. Nuclear Reactor Orders and Construction Time

<i>Decade</i>	<i>Number of reactors ordered</i>	<i>Percent eventually completed</i>	<i>Construction time (in years) for completed reactors</i>		
			<i>Average</i>	<i>Minimum</i>	<i>Maximum</i>
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.

per kilowatt of capacity. The figure reveals a pronounced increase in construction costs, particularly for plants completed during the 1980s.³

Plants also kept taking longer and longer to build. As shown in Table 1, reactors ordered during the 1950s took on average about five years to build, whereas reactors ordered during the 1970s took on average 14 years. 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. Regulation also contributed directly to construction costs. The Nuclear Regulatory Commission implemented revised safety codes and inspection requirements leading in several cases to extensive reactor redesigns (Cox and Gilbert 1991; McCallion 1995).

An interesting point of comparison is France. After the United States, France has more nuclear reactors than any other country, and 75 percent of electricity generation in France comes from nuclear power. Grubler (2010) finds that 58 reactors in France's main nuclear program were constructed at an average cost that increased over time from \$1,000 per kilowatt of capacity in the 1970s to \$2,300 in the 1990s. The cost escalation is less severe than is observed in the United States, but still somewhat surprising. As I discuss later, in many ways the French nuclear program was the ideal setting for encouraging learning-by-doing, so one might have expected costs to decrease over time.

Financing Risks

The long period of time required for construction means that the cost of capital is a critical parameter for evaluating the viability of nuclear power. Even for a low

³ See Koomey and Hultman (2007) for a more recent study of U.S. nuclear construction costs, and Mooz (1978), Komanoff (1981), and Zimmerman (1982) for studies of the earlier period. Joskow and Rose (1985) examine increases in construction costs for coal plants during the 1960s and 1970s finding significant cost increases associated with measurable environmental-related technologies such as scrubbers and cooling towers, as well as a large increase in residual real costs that they attribute to changes in environmental regulation and to an unexplained decline in construction productivity.

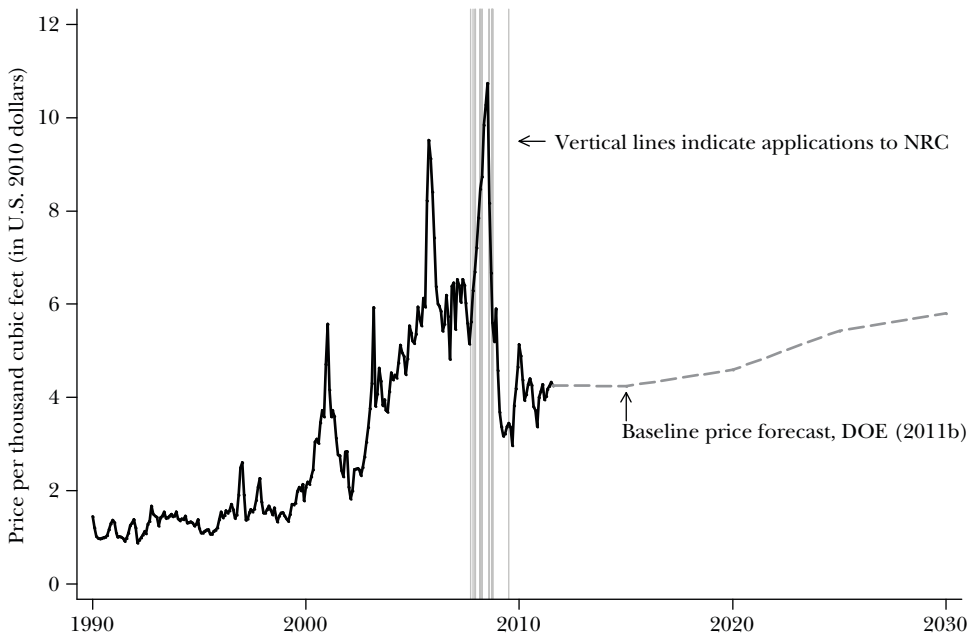
cost of capital, the extended construction period imposes financing costs that are a substantial part of total project costs. However, nuclear projects typically face a cost of capital well above the risk-free rate. These large-scale projects have a historically high risk of default. The high cost of capital that they face reflects the number of risks that threaten the profitability, and even viability, of a nuclear project.

More so than in most other investments, nuclear power plants face substantial regulatory risk. The Nuclear Regulatory Commission 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. It remains to be seen how these procedures will work in practice. Regulatory approval is also required at the state and local level, and it can be 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 percent completed and had been connected to the grid, yet was never used to produce a single kilowatt hour of commercial electricity.

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 so when the key legislative vehicle (H.R. 2454, the “Waxman–Markey bill”) stalled in the U.S. Senate in 2009, it was a significant blow to the economic viability of new nuclear plants. In the last few years, 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 that do not generate carbon emissions. Such a policy could be a considerable boost for nuclear power, but the exact form of such legislation, or how likely its adoption would be, is unclear.

Investors in nuclear power also face the risk that fossil fuel prices could 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 plants that sell power in wholesale electricity markets. Global availability of natural gas has increased dramatically in recent years with improvements in horizontal drilling and hydraulic fracturing technology. Natural gas producers have long known that shale and other rock deposits contain large amounts of natural gas. It was not until recently, however, that these resources could be accessed at reasonably low cost.

Figure 4 plots U.S. natural gas prices from 1990 to 2011 and a price forecast through 2030. During the long period of relatively low natural gas prices, there was not a single new nuclear plant ordered in the United States, and the surge in orders in 2007 and 2008 came at the same time that U.S. natural gas prices reached their highest level ever in real terms. The baseline forecast from U.S. Department of Energy (2011b) predicts that U.S. natural gas prices will remain under \$5 per thousand cubic feet through 2022. If true, this is a significant challenge for nuclear power.

*Figure 4***U.S. Natural Gas Prices and Applications to the U.S. Nuclear Regulatory Commission (NRC)**

Sources: Author based on data from U.S. Department of Energy (2011a, b) and U.S. Nuclear Regulatory Commission (2011).

Finally, investments in nuclear power face considerable technology risk. Over the 40-plus year lifetime of a nuclear plant, the available sources of electricity generation could change considerably. An alternative, lower-cost technology could come along, or perhaps a technology that is known today such as wind or solar could quickly become more cost effective. An alternative technology for carbon abatement could become practical, like some form of carbon capture and storage, which would render moot one of the advantages of nuclear power. New energy efficiency technologies might reduce electricity demand.

Recent International Experience

More recent evidence on construction costs comes from nuclear reactors currently being built in Olkiluoto, Finland, and Flamanville, France. Much has been written about these reactors because they are the first new reactors to be built in Europe in many years, and because they use a “next generation” design that incorporates several new safety features into a reactor design that is widely used around the world. Construction in Finland began in 2005 and was expected to

Table 2

Power Plant Construction Costs Excluding Financing for Nuclear, Coal, and Natural Gas

Source	Cost per kilowatt of capacity (in year 2010 dollars)		
	Nuclear	Coal	Natural gas
MIT (2009)	\$4,200	\$2,400	\$ 900
U.S. Department of Energy (2010)	\$5,300	\$2,800	\$1,000

be completed in 2009 at cost of about \$2,800 per kilowatt of capacity. 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 in France began in 2007 and the reactor was expected to be completed by 2011 at a cost of \$2,900 per kilowatt. Completion has now been pushed back to 2014 and the project is reported to be 50 percent over budget.

These experiences provide a reminder about problems that can occur during reactor construction, particularly given the lack of recent construction experience. Both projects were delayed substantially when government 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.

Construction costs have tended to be lower elsewhere. Du and Parsons (2009) report a mean overnight cost of \$3,100 per kilowatt from five reactors completed in Korea and Japan between 2004 and 2006. Construction costs from plants recently completed in China are reported to be even lower and an important area for future research is to examine these costs in detail.

Several studies have attempted to synthesize this recent international construction experience with historical U.S. data and engineering studies to estimate current construction costs for the United States. Table 2 reports estimates of overnight construction cost from two such studies. MIT (2009) estimates \$4,200 per kilowatt of capacity for nuclear, compared to \$2,400 and \$900 per kilowatt of capacity for coal and natural gas. U.S. Department of Energy (2010) 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 only a limited set of construction firms have 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 recently elevated regulatory scrutiny.

Adding financing costs to these estimates implies that a typical two-reactor 2,000 megawatt plant could cost more than \$12 billion. The long period of time since nuclear power plants were constructed in the United States means that the

relevant experience that had been accumulated by companies involved with nuclear engineering and plant construction has atrophied substantially (Joskow and Parsons 2009). There is some scope for importing nuclear engineers and other professionals who have worked on more recent nuclear projects in other countries, but the overall level of nuclear construction activity worldwide over the last 20 years has been so low that the available global talent is limited. Moreover, the supply of nuclear plant components is now more limited than it was during the first wave of nuclear power plant construction. For example, there is currently 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).

These construction cost estimates contain considerable uncertainty, which 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. One of the economic arguments made in support of the subsidies for new nuclear plants in the 2005 Energy Policy Act was that they would help resolve this uncertainty about construction costs.

Levelized Cost Estimates

The total cost of producing electricity depends both on construction costs and on operations and maintenance expenditures, including fuel. These variable costs tend to be low for nuclear, potentially offsetting the higher cost of construction. Table 3 reports “levelized” costs for electricity generated in the United States from nuclear, coal, and natural gas, the three primary forms of baseload electricity generation. These estimates are based on a cash flow model developed in an ongoing series of studies at the Massachusetts Institute of Technology (MIT 2003; MIT 2009; Joskow 2006; Du and Parsons 2009; Joskow and Parsons 2009). For these estimates, all costs including construction, operation, maintenance and fuel 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 long-run average 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 break even.

Under the baseline assumptions, nuclear is not competitive with either coal or natural gas. The first row of Table 3 reports the base case estimates reported in MIT (2009). The levelized cost of nuclear power is 8.7 cents per kilowatt hour, compared to 6.5 cents for coal and 6.7 cents for natural gas. This gap widens in the second row after updating these estimates to reflect higher construction cost estimates from U.S. Department of Energy (2010). The third row updates the estimates to reflect changes in fuel prices since 2009. Uranium prices have increased modestly, but fuel expenditures represent a relatively small proportion of the total cost of nuclear power, and at this higher price, even after including costs for conversion,

Table 3
Levelized Cost Comparison for Electricity Generation

<i>Source</i>	<i>Levelized cost in cents per kWh</i>		
	<i>Nuclear</i>	<i>Coal</i>	<i>Natural gas</i>
MIT (2009) baseline	8.7	6.5	6.7
Updated construction costs	10.4	7.0	6.9
Updated construction costs and fuel prices	10.5	7.4	5.2
With carbon tax of \$25 per ton CO ₂	10.5	9.6	6.2

Source: These calculations follow MIT (2009) except where indicated in the row headings.

Notes: All costs are reported in 2010 cents per kilowatt hour. Row 1 reports the base case estimates reported in MIT (2009), table 1. The cost estimates reported in row 2 incorporate updated construction cost estimates from U.S. Department of Energy (2010). Row 3, in addition, updates fuel prices to reflect the most recent available prices for uranium, coal, and natural gas reported in U.S. DOE (2011a). Finally, row 4 continues to incorporate updated construction costs and fuel prices and, in addition, adds a carbon tax of \$25 per ton of carbon dioxide.

enrichment, and fuel fabrication, nuclear fuel costs are still less than one cent per kilowatt hour. 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). Fossil fuel prices are extremely important for the prospects for nuclear power, and the cost estimates in the third row reflect somewhat higher coal prices but also considerably *lower* natural gas prices. With these updated prices, the levelized cost of electricity from natural gas is just above 5 cents per kilowatt hour, compared to more than 10 cents per kilowatt hour for nuclear.

These estimates follow the MIT studies in applying a somewhat higher cost of capital to nuclear power. As discussed earlier, this reflects the high risk of default and numerous forms of risk faced with nuclear projects. It is worth noting, however, that even without this risk premium, nuclear still has higher levelized cost than coal or natural gas. The model also assumes a 40-year lifetime for nuclear, coal, and natural gas plants. Over half of U.S. nuclear plants have received license extensions to 60 years. Incorporating a longer lifetime into the model makes nuclear look better, but not by very much. The increased net revenue is far in the future so with discounting there is only a modest decrease in levelized costs. Moreover, coal and natural gas plants are also tending to be used for more than 40 years, and one would want to incorporate those longer lifetimes as well.

It is important to emphasize that these levelized cost estimates depend on a series of empirical assumptions, many of which can be only partially verified. Perhaps most importantly, alternative assumptions about nuclear construction costs or natural gas prices can begin to change the outlook considerably. Moreover, these cost estimates are for the United States and may not easily generalize to other countries. Construction costs vary substantially across countries due to differences in the cost of labor and other inputs, as well as differences in the regulatory environment.

Another key factor is the availability of natural gas. Global capacity to transport liquefied natural gas is increasing rapidly but is still insufficient to have eliminated price differences across countries.

Incorporating Externalities

Levelized cost estimates are typically designed to reflect the *private* costs of investing in different forms of electricity generation. Thus they provide a basis for determining whether different types of plants *will* be built, but not necessarily for determining whether different types of plants *should* be built.

The fourth row in Table 3 incorporates a tax of \$25 per ton of carbon dioxide. As a point of comparison, the Federal Interagency Working Group (2010) adopts a central social cost of carbon dioxide of \$25 for 2015. Under this scenario, nuclear continues to have the highest levelized cost. The levelized cost of coal increases by 2 cents per kilowatt hour, but the levelized cost of natural gas increases by only about 1 cent, not nearly enough to close the gap between nuclear and natural gas. Moreover, this static comparison based on current fuel prices ignores that coal and natural gas prices would likely fall in response to a carbon tax. For both coal and natural gas there is a range of different sources available, much of which has a marginal cost of extraction below current prices.

Fossil fuel plants also emit large amounts of local and regional pollutants. Muller, Mendelsohn, and Nordhaus (2011) calculate that the external costs from sulfur dioxide, nitrogen oxides, and particulates average 3.5 cents per kilowatt hour for coal, but only 0.1 cents per kilowatt hour for natural gas. Thus, incorporating the external costs of these pollutants improves the prospects considerably for nuclear power versus coal, but does little to close the gap versus natural gas. A comprehensive welfare analysis would also incorporate the negative production externalities from coal and natural gas. Perhaps most importantly, recent increases in shale gas production have raised environmental concerns about water consumption and contamination of drinking water. These costs are not yet well understood. However, the levelized cost estimates give some sense of how large these externalities would need to be in order to make nuclear power the low-cost option.

There are also external costs associated with nuclear power. Included in these levelized cost estimates is a spent fuel waste fee of 0.1 cents per kilowatt hour. Since 1983, the Department of Energy has collected this fee from U.S. nuclear reactors, intended eventually to finance a centralized storage facility for spent nuclear fuel. Currently, most spent nuclear fuel is stored on-site in spent fuel pools and dry casks. A comprehensive welfare analysis would need to include both the private and external costs of this on-site storage. MIT (2010) and U.S. Nuclear Regulatory Commission (2011) discuss details of the nuclear fuel cycle.

Considerably harder to quantify are the risks from nuclear accidents. Since 1957, the Price–Anderson Act has indemnified U.S. nuclear plant operators from accident liability above a certain cap, currently \$12 billion. A Fukushima-type

accident in the United States could easily cause damages well above this cap. It is too early to measure the long-term external costs of Fukushima, but an early study estimates that radioactive contamination could cause 1,000 total cancer deaths (von Hippel 2011). As a point of comparison, cancer deaths from Chernobyl are estimated to be approximately 14,000 (Cardis et al. 2006). In addition to cancer deaths, one would want to incorporate the costs from other health outcomes, as well as the pecuniary and psychological costs associated with relocating people living near the accident site.

Perhaps hardest of all to measure are the risks associated with the proliferation of nuclear weapons. This could come through the misuse of nuclear facilities to produce weapons materials, or from a “dirty bomb” in which stolen radioactive materials from any source are dispersed using conventional explosives. These risks are particularly acute in countries like France, the United Kingdom, and Japan that have facilities for reprocessing nuclear waste. MIT (2003) and MIT (2010) discuss these issues.

Incorporating the external costs of nuclear power would further increase the gap between the levelized costs of nuclear and natural gas. An important priority for future work is to refine measures of these external costs and incorporate them explicitly into levelized cost analyses. However, given current market conditions in the United States, it becomes difficult to make an economic argument for nuclear power regardless of the magnitude of these external costs. The first challenge continues to be construction costs, which are high enough that nuclear power struggles to compete with natural gas even if one ignores these external costs completely.

Learning-By-Doing

What would it take to reduce nuclear construction costs? One possibility is learning-by-doing. In 2004, the Senior Vice President of the Nuclear Energy Institute testified in front of the U.S. Senate that nuclear construction costs would decrease by 20–30 percent after the first few plants (Fertel 2004). In part on the basis of this testimony, the 2005 Energy Policy Act was drafted to include loan guarantees, production tax credits, and other subsidies for new nuclear plants. If learning-by-doing could push construction costs down, this could change the equation considerably for nuclear power. 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 2011), and several studies have examined learning-by-doing in the construction of nuclear power plants.

Recall that the time pattern of construction costs in Figure 3 did not provide any immediate evidence of learning-by-doing. Instead, construction costs tended to *increase* considerably over time. Several studies have nonetheless attempted to disentangle learning-by-doing from industrywide factors that were changing over time. Using data from the early nuclear builds, 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 industrywide learning-by-doing. Zimmerman (1982) also finds learning-by-doing for the construction company and some evidence of spillovers across companies. Using a longer panel, McCabe (1996) finds evidence of learning-by-doing for both the construction company and the utility managing the project, but does not test for industrywide learning.

Learning-by-doing is important for the prospects of nuclear power because it provides a plausible mechanism by which nuclear construction costs could decrease below the levels reported in Table 2. This is true regardless of whether or not this learning-by-doing is privately captured. Who captures the learning-by-doing is important, however, for government policy. The economic argument for an industry-specific subsidy hinges on there being learning-by-doing that is not captured by individual companies. If learning is fully appropriable, then firms face efficient incentives for investment and no government intervention is necessary. In addition, while there is almost certainly some industrywide learning-by-doing in nuclear, there is also likely to be learning-by-doing in emerging energy technologies such as wind, solar, and biomass. When there are a number of competing alternatives, as in electricity generation, many economists favor broad-based subsidies that do not single out individual technologies (Schmalensee 1980).

Tied up in this discussion is a key tradeoff between innovation and standardization. On the one hand, it is important to continue allowing for new and better reactor designs with enhanced features for reliability and safety. On the other hand, frequent redesigns make it harder to spread engineering costs across projects. The first wave of U.S. reactors were manufactured by four different companies—Westinghouse, General Electric, Combustion Engineering, and Babcock & Wilcox—each with several different designs. At the time, such differences were inevitable. The United States led the way in the development of commercial nuclear reactors and the technology was evolving rapidly. Still, this diversity of designs provides a possible explanation for the lack of immediate evidence of learning-by-doing (Lester and McCabe 1993).

France offers a useful comparison on this point. Development of nuclear power in France began later and with much less design variation. When Electricité de France began seriously building reactors in the 1970s, it adopted a single design for all of its reactors. With one exception, all nuclear power reactors currently in operation in France are of exactly this same design (International Atomic Energy Agency 2011). In addition, Electricité de France has long enjoyed a high degree of regulatory stability due to its close relationship with the French National Safety Authority and broad public support for nuclear power. Given this high degree of standardization, the apparent cost *escalation* in French construction costs is particularly striking.

Some within the U.S. nuclear industry claim that the United States is headed more toward the French model. For example, Michael Wallace, chairman of a major nuclear power company predicted a couple of years ago (as quoted in Kanter 2009)

that new reactors would be standardized down to “the carpeting and wallpaper.” Perhaps the industry will quickly coalesce around a very small number of reactor designs, but this is not obvious based on applications received to date by the Nuclear Regulatory Commission. Among the 17 applications that have been received, there is a mix of both pressurized water reactors and boiling water reactors, manufactured by five different reactor manufacturers (Areva, Westinghouse, Mitsubishi, GE-Hitachi, and GE). At a minimum, it seems clear that the French approach of supporting a single reactor design is not going to be adopted in the United States.

Conclusion

Nuclear power continues to generate enthusiasm based on its potential to reduce greenhouse gas emissions. 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 a year.⁴ While burning 16,000 pounds of coal generates thousands of pounds of carbon dioxide, sulfur dioxide, and nitrogen oxides—nuclear power is virtually emissions-free.

Nuclear power, however, is not without challenges. Fukushima has brought to the forefront ongoing concerns about nuclear accidents and the handling and storage of spent fuel. These external costs are *in addition* to substantial private costs. 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.

■ *I am thankful to David Autor, Severin Borenstein, Chad Jones, John List, John Parsons, Timothy Taylor, Catherine Wolfram, and seminar participants at the University of Tennessee, Brookings Institution, University of California Energy Institute, Berkeley Energy and Resources Collaborative Symposium, California Public Utilities Commission, and the University of Chicago for helpful comments.*

⁴This is my own back-of-the-envelope calculation based on U.S. Department of Energy (2011a), 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.”

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