Article 6: Economics

Economic competitiveness is a challenge for nuclear power, particularly in liberalized electricity markets where utilities compete to meet a given demand by supplying power at the lowest cost. We address two related questions: 1) How competitive is nuclear power? 2) What will determine how well small modular reactors will compete against large nuclear reactors?

How competitive is nuclear power?

The main component of the cost of generating power at a nuclear plant, no matter what the size of the plant, is the capital cost of constructing the nuclear reactor. Many costs are proportional to the capital cost, including project financing costs, depreciation, insurance, taxes, and interest during construction. We combine these costs and annualize them by multiplying the capital cost by a constant levelized capital charge rate of 15 percent per year – a typical factor in power plant cost estimation. Cost components that are recurrent and not directly related to the capital cost include the costs of the fuel and operating costs. We obtain a total annualized cost for the power produced at the plant by combining the annualized capital-related cost and the annual recurrent capital-independent costs, and we obtain the cost of electricity by dividing this sum by the amount of power the plant produces in a year. Our estimate entails many simplifications, including neglecting two difficult-to-quantify costs associated with nuclear power: the cost of dealing with the radioactive waste products, and the cost of setting aside money to clean up the site after the reactor has been retired.

The construction cost for a new nuclear power plant is highly uncertain. The costs of plants constructed in the past have varied widely, and the variations can be explained only in part by the amount of previous experience, interest rates, land prices, site-specific factors, and regulatory stringency. One source of cost estimates for future plants is an "expert elicitation" conducted by Carnegie Mellon University in 2013. This elicitation presented a set of questions to 16 people with significant experience in nuclear reactor manufacture and made special efforts to control for bias and overconfidence. The elicitation focused on assessing the "overnight capital cost," defined as the sum of engineering, procurement, and construction costs, and excluding financing of construction, site work, transmission upgrades and other "owner's costs." Cost estimates were requested in 2012 dollars and were to be not for the first plant built but for a plant that "has recouped the cost of design engineering and licensing, has exploited technological learning, and has streamlined construction management." It was further specified that the plants were to be built in the southeastern United States "under a 'favorable' regulatory environment, overseen by a regulator such as the U.S. Nuclear Regulatory Commission (NRC)." With this guidance, for 13 of the 16 respondents the median estimate of the overnight construction cost was between $4,100 per kilowatt and $6,100 per kilowatt.

The estimates elicited from these experts must be balanced against the long history of construction costs and construction times ending up substantially higher than estimates in the pre-construction phase. An example is the Vogtle nuclear reactor under construction in the U.S. state of Georgia, where the project is already delayed by at least 18 months and estimated capital costs that initially were about $6,000 per kilowatt are now over $7,300 per kilowatt.

We invoke a rule of thumb, that when the cost of construction of a nuclear plant is $4,000 per kilowatt, the capital-related costs represent two-thirds of the cost of electricity and the capital-independent costs account for the remaining one-third. Thus, for such a plant, the annualized cost for capital-related costs, per kilowatt of capacity, is $600 per year (15 percent per year times $4000 per kilowatt of capacity) and the capital-independent costs are $300 per year. We assume that whether the cost of construction is more or less than $4,000 per kilowatt, the other costs per kilowatt are still $300 per year. We ask how well such a reactor can compete against alternative sources of electricity.

Today's nuclear power plants are operated at or close to full power for 80 to 95 percent of the time, with planned shutdowns typically once every 18-24 months for fuel replacement. Accordingly, the most obvious cost comparisons are with other systems that can operate at full power nearly all of the time – so called "baseload" power plants. It is more complicated to compare nuclear plants with wind power or solar power, which produce electricity intermittently.

We choose as our baseload alternative a natural gas plant that is designed to run nearly all of the time at high efficiency, a so-called "combined-cycle" natural gas power plant. We assume that its installed capital cost is $1,000 per kilowatt of capacity, or, annualized and per kilowatt, $150 per year. We also assume that the only significant cost for baseload electricity from natural gas, other than capital, is the cost of the natural gas itself. And we assume that the natural gas plant converts 50% of the energy in natural gas into electricity. The calculation requires some artful arithmetic, because the price of natural gas is usually reported in dollars per million British thermal units (Btu) of energy. The associated component of the cost of the electricity, per year per kilowatt, for the natural gas power plant is 60 times the cost of natural gas in Btu units. For example, if natural gas costs $5 per million Btu (somewhat higher than the current price of natural gas in the U.S.), the cost per year of one kilowatt of power from the natural gas plant is $450: $150 for the capital cost of construction (annualized) and $300 for the natural gas.

With these assumptions we can identify the construction cost for a nuclear power plant that produces electricity at the same cost as a natural gas power plant, for a given price of natural gas. For natural gas at $5 per million Btu, the breakeven capital cost of the nuclear power plant is $1,000 per kilowatt; at that cost, the cost per year for nuclear electricity is also $450: $150 for the annualized capital and $300 for the capital-independent costs. A capital cost of $1000 per kilowatt, the expert elicitation referred to above informs us, is far less than anticipated construction costs for nuclear power plants. However, if natural gas costs $15 per million Btu (approximately the cost today of liquefied natural gas delivered by ship in Japan), the breakeven capital cost for nuclear power is $5,000 per kilowatt, which is within the range of expected construction costs. For every increase of $5 per million Btu in the price of gas, the breakeven construction cost for the nuclear power plant increases by $2,000 per kilowatt.

A carbon tax would make nuclear power a stronger competitor with power from natural gas. It turns out that a carbon tax of $100 per metric ton of carbon dioxide will increase the price of natural gas by approximately $5 per million Btu. Thus, a tax of this magnitude would raise the breakeven construction cost for the nuclear power plant by $2,000 per kilowatt. If the price of natural gas is $10 per million Btu (approximately the price in Western Europe), the breakeven construction cost for nuclear power would be $3,000 per kilowatt in the absence of a carbon price, but $5,000 per kilowatt in the presence of a tax of $100 per metric ton of carbon dioxide. $3,000 per kilowatt is below the costs estimates from the expert elicitation, but $5,000 per kilowatt is not (see Figure 6.1).

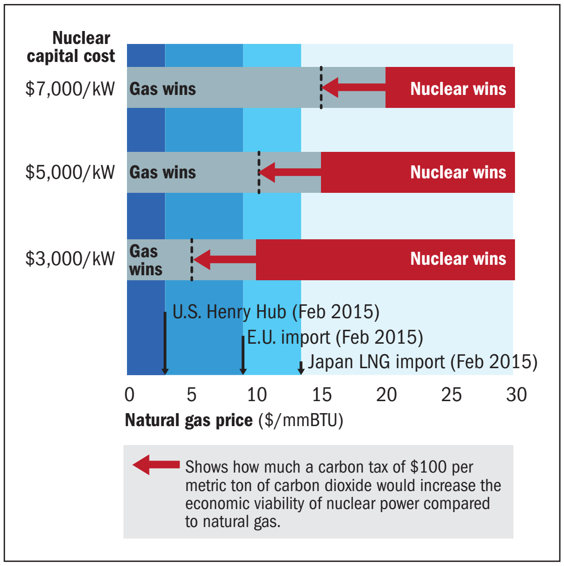

Figure 6.1: Nuclear power versus constant-power natural gas, for various gas prices and nuclear power capital costs, without and with a $100 per metric ton price of carbon dioxide.

What will determine how well small modular reactors will compete against large nuclear reactors?

A key economic challenge for small modular reactors is to compete with large nuclear reactors that provide the same capacity. Two effects influence the comparison in opposite ways: economies of scale and economies of serial production. For the same capacity, economies of scale can make a larger plant cheaper than a smaller plant. But economies of serial production can make a smaller plant cheaper, if small plants are produced in large numbers.

Economies of scale

The history of nuclear power can be understood as driven by the cost savings from bigness: in the 1950s and 1960s, nuclear reactors had power levels of 100 megawatts or less, but many of the reactors under construction today generate more than 1,000 megawatts, and some of the larger ones generate more than 1,500 megawatts. Economies of scale arise for both capital and operating costs. A 400-megawatt reactor does not need twice as much concrete or steel as a 200-megawatt reactor or require twice as many operating personnel. One way to visualize the scale economy is to compare the costs of transporting a group of 10 people: The cost of transporting the group in a large van is smaller than the cost of transporting each individual in a separate taxi, because a van does not cost 10 times as much as a car, nor does it need 10 drivers.

Such an analogy assumes that all 10 people need the transport services. The corresponding assumption is that all the electricity generated will be purchased. The market for electricity may be too small to justify a large reactor. The flexibility arising from phased construction of small modular reactors may outweigh a cost disadvantage when future demand for electricity is uncertain.

Since small modular reactors have an output electrical power of less than 300 megawatts, they are expected to suffer diseconomies of scale and therefore to have higher capital and operating costs per megawatt of capacity, when compared to the large reactors currently under construction or contemplated for construction.

Economies of serial production

Fewer large reactors than small reactors would need to be constructed to generate the same amount of electrical power. If many identical small modular reactors were constructed in a single factory, it is likely that unit costs would come down as a result of learning. Learning effects are well studied across many industries, including the nuclear industry. These effects are typically quantified by a "learning rate," the relative reduction in cost of construction, in percentage points, accompanying every doubling of the cumulative number of units. If a certain industry shows a learning rate of 10 percent for a technological product whose unit cost is $1,000 after construction of 3,000 units, it would be able to build its 6,000th unit for a price of $900.

A calculation displaying the trade-off between economies of scale and economies of serial production

It is by no means obvious that the methods used elsewhere in industry to quantify economies of scale and economies of serial production are appropriate for comparing small and large nuclear power plants. For one, there are significant differences in their designs: a small modular reactor is typically not just a scaled-down large reactor. Moreover, above some size, economies of scale are no longer realized: an airplane that has become too large to use existing runways, for example.

Similarly, there are reasons to doubt the usual models of economies of serial production. Below some number of production units, economies of serial production are not realized, because not enough experience has been gained to make further production routine. Furthermore, economies of serial production may not exhibit the same percentage cost reduction with doubled production for early doublings and late doublings (e.g., expanding from 300 to 600 units and later from 30,000 units to 60,000 units).

Nonetheless, existing tools can provide insights. Specifically, we calculate the number of small units that have to be built in order for the learning effects to cancel out the effects of diseconomies of scale.

All else being equal, the costs of two nuclear reactors with different power capacities but otherwise similar design will be related as the ratio of their power capacities raised to some exponent. Although there is no consensus in the literature regarding the appropriate exponents for economies of scale, an illustrative value for the exponent is 0.6. This relationship is a rule of thumb, not an exact estimate, but evidence for such scaling behavior is observed in many industries. To take a specific example, imagine that the capacities of the large and small reactors are 1,000 and 200 megawatts, respectively. Using 0.6 as the exponent in the rule, the cost of the 200 megawatt plant is not five times less but about 2.5 times less. As a result, the capital cost of producing 1,000 megawatts of power from five of the small plants is twice the cost of producing 1,000 megawatts from the large plant. Operations and maintenance costs also have a similar scaling behavior; that is, these costs too do not increase in linear proportion to the power output. Because the designs of many small modular reactors differ from the designs of their counterpart larger reactors in significant ways—for example, not using large pipes because steam generators are inside the pressure vessel (see Article 3)—scaling using an exponent of 0.6 must be considered only a crude approximation.

As for learning rates for nuclear power plants, analysts often use estimates in the range of 5 to 10 percent, even though in the two countries with the most reactors, the United States and France, learning has been negative and costs have increased with greater experience in construction. In the case of the United States, the cost escalation results in part from regulatory changes, in part from discovering more safety concerns, and in part from building custom-designed reactors, rather than reactors sharing the same design. How much learning will be possible with small modular reactors is difficult to predict in advance of extensive construction experience.

We work with an example. We combine a scale economy characterized by an exponent of 0.6 and a learning rate of either 10 percent or 5 percent for the small plants, a rate which comes into effect once 10 small plants have been produced. We further assume that there is no learning for the larger plants and that the capacities of the large and small plants are 1,000 and 200 megawatts, respectively. The result: with a learning rate of 10 percent, after 700 small plants have been produced they no longer cost more per kilowatt than a large plant: cost reductions from learning have overtaken cost penalties for smallness. With a slower learning rate of 5 percent and the other assumptions unchanged, the costs of large and small units cross only after 60,000 small units have been produced. This calculation illustrates the strong sensitivity of the crossover cost to the learning rate and the critical importance of fast learning for the competitiveness of small modular reactors. A slower learning rate for small modular reactors will result, for example, if several different reactor designs are deployed and none ends up dominating the marketplace.

Other considerations

Several considerations not yet discussed work to the advantage of a small reactor. The initial investment required to build a single small reactor will be considerably lower than that required to build a typical large reactor, possibly making it easier to borrow the necessary capital from financial markets. A lower construction cost also permits a utility to risk a smaller fraction of its capital on a single nuclear project. A shorter construction time reduces the costs of paying interest to lenders during the construction period. Longer construction periods have been a major factor responsible for cost escalation for nuclear reactors. The same expert elicitation described above estimates a shortening of the construction period from five years to three years. These experts, however, see substantial complications in any single facility that integrates several small units, because of complexities during the licensing phase, during construction, during routine operation, and during accidents.