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Citation: Joskow, Paul L., and John E. Parsons. "The economic future of nuclear power." *Daedalus* 138.4 (2009): 45-59.

As Published: <http://dx.doi.org/10.1162/daed.2009.138.4.45>

Publisher: American Academy of Arts and Sciences

Persistent URL: <http://hdl.handle.net/1721.1/51889>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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The economic future of nuclear power

In the last several years we have seen what appears to be revived global interest in continuing operation of existing nuclear power plants and constructing a new generation of plants.¹ A recent International Atomic Energy Agency (IAEA) report indicates that 24 countries with nuclear power plants are considering policies either to accommodate or encourage investments in new nuclear power plants, and that 20 countries without nuclear power today are considering supporting the use of nuclear power to meet future electricity needs. It projects as much as a 100 percent increase in nuclear generating capacity by 2030.² The United States has taken a number of steps to encourage investment in a new fleet of nuclear power plants. The federal safety review and licensing process has been streamlined, and a variety of financial incentives for new nuclear plants are included in the Energy Policy Act of 2005. As of early 2009, license applications for 26 new plants have been filed with the U.S. Nuclear Regulatory Commission (NRC), and additional applications are likely.³

This renewed interest appears to reflect a variety of considerations, including a shift toward sources of electricity that do not produce CO₂; the search for lower-cost sources of electricity, stimulated by dramatic increases in fossil fuel prices prior to the

¹ The views expressed here are those of the authors and not of the Alfred P. Sloan Foundation or the Massachusetts Institute of Technology.

² *International Status and Prospects of Nuclear Power* (Vienna, Austria: International Atomic Energy Agency, 2008). Unless otherwise referenced, the information in this paper about the status of nuclear power in various countries is from this report or from the IAEA's online PRIS data sets, available at www.iaea.or.at/programmes/a2/.

³ U.S. Nuclear Regulatory Commission, www.nrc.gov/reactors/new-reactors/col.html.

current global economic contraction; and (often poorly defined) energy security concerns associated with fossil fuels, especially natural gas.

The potential revival of nuclear power faces a number of risks and challenges that make the anticipated “renaissance” of nuclear power in the United States and other countries quite uncertain. The economics of maintaining the existing fleet of nuclear power plants, investment in new nuclear power plants, and the economic impacts of constraints on CO₂ emissions, not to mention considerations of safety, waste disposal, proliferation, and spent-fuel reprocessing: all impact the feasibility of a nuclear power renaissance.

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There are 436 nuclear power plants operating in 30 countries, with combined generating capacity of about 370,000 megawatts of electricity. These plants accounted for about 14 percent of global electricity generation in 2007. The contribution of nuclear power to meet electricity demand varies widely from country to country. For example, in France, 59 nuclear plants generate about 77 percent of the country’s electricity; in Japan, 53 plants generate 27 percent of the electricity; and in the United States, 104 plants generate just under 20 percent of electricity. Together, these three countries account for about 57 percent of global nuclear power capacity. In China and India, nuclear power accounts, respectively, for 2 percent and 2.5 percent of the electricity generated there today.

The existing fleet of nuclear power plants is fairly old. About 92 percent of this nuclear capacity is more than 10 years old, and 78 percent is more than 20 years old. This age distribution reflects the fact that almost 30 years ago, developed countries effectively stopped making commitments to build new nuclear plants. (France and Japan are

exceptions in this regard.) The most recent nuclear plant completed in the United States began generating electricity in 1996, though construction on it began in 1973. Sweden's most recent operating nuclear plant went into service in 1985, Germany's in 1989, Canada's in 1993, and the United Kingdom's in 1995. Following the 1979 incident at Three Mile Island, Sweden passed a law in 1980 banning the construction of new nuclear plants and requiring a gradual closing of existing nuclear plants. After the Chernobyl incident in 1986, two reactors were closed, in 1999 and 2005. Italy had four commercial nuclear power plants, but shut them down after a referendum in 1987. In 2000, Germany officially announced its intention to phase out nuclear power gradually over time, and two reactors were subsequently closed as part of this process. Other countries, including Spain and the United Kingdom, implemented de facto bans on building new nuclear plants. Most of the global nuclear capacity completed in the last decade is located in Japan, South Korea, China, and India.

The early history of the existing fleet of nuclear plants, especially in the United States, is not a happy one. Many nuclear plants experienced significant construction delays and cost overruns. Many plants planned during the 1970s were abandoned before construction started; some were abandoned after construction began but before completion. Nuclear plants are quite capital intensive. If they are to be economical to build, they must be able to supply electricity for a large fraction of the hours of the year (85 to 90 percent). However, the early operating experience of the existing fleet was poor. For example, in 1985, the capacity factor of nuclear power plants in the United States was only 58 percent.⁴ Even today, after a long, steady trend in improvement, the *lifetime* capacity factor of U.S. nuclear plants is only about 78 percent. Capacity factors

⁴ U.S. Energy Information Administration, *Annual Energy Review 2007*, Table 9.1.

vary widely from country to country. The lifetime capacity factor is 91 percent in Finland, 86 percent in Switzerland, 73 percent in the United Kingdom, and 75 percent in Canada.⁵ Because non-fuel operation and maintenance costs of a nuclear plant are largely fixed, the low capacity factors drove up the operating costs per unit of electricity produced from nuclear plants. Despite being more capital intensive, for many years even the operating costs per unit of electricity produced were higher for nuclear plants in the United States than for coal plants.⁶

Other factors also played a role in the abandonment, since 1980, of commitments to build new nuclear plants in many countries. The price of fossil fuels fell dramatically after its peak in the early 1980s and remained relatively low until 2003. Abundant supplies of cheap natural gas and improvements in thermal efficiency associated with gas combined-cycle generating technology (CCGT) made construction of new CCGT plants attractive alternatives in many countries. In countries with low-cost coal reserves, the relatively low price of coal made coal-fueled generating capacity more attractive than nuclear, despite tightening environmental requirements placed on coal plants.

* * *

A number of changes have taken place over the last few years that have led a growing number of countries and investors to view nuclear power more favorably than was the

⁵ We rely on data for both capacity factors and energy availability factors depending on the data available for different countries. A nuclear plant's capacity factor is the ratio of the actual electricity generated divided by the maximum quantity of electricity that could be produced if the plant ran at its capacity for every hour of the year. A plant's energy availability factor is the amount of electricity that a plant is "available" to produce (that is, it is not out of operation due to maintenance or refueling outages) divided by the amount of electricity a plant could produce if it operated at full capacity to produce electricity every hour of the year. Because nuclear plants have low marginal production costs, they are typically producing electricity whenever they are available. Accordingly, the capacity factor and the energy availability factor for a plant are generally very close to one another. We use the term "capacity factor" to refer to data for both capacity factors and energy availability factors.

⁶ Nuclear Energy Institute, www.nei.org/resourcesandstats/documentlibrary/reliableandaffordableenergy/graphicsandcharts/uselectricityproductioncosts/.

case a decade ago. First, the performance of nuclear plants has improved markedly in the last two decades. These improvements have probably been most dramatic in the United States, and we will focus on the U.S. experience here. Nuclear plant capacity factors in the United States have increased steadily over the last two decades, and the average now hovers around 90 percent. The time required to reload fuel fell from about 100 days in 1990 to about 40 days today. Average nuclear plant operating costs, adjusted for inflation, have declined slowly but continuously over the last two decades. The average operating cost per unit of electricity produced is now significantly lower for a typical U.S. nuclear plant than for a typical coal plant, much lower than for a conventional gas- or oil-fueled steam turbine, and lower than for a modern CCGT, with gas prices above about \$4/MMBtu.⁷ Safety metrics in the United States have also improved significantly in the last two decades, and organizations that review nuclear plant safety through a detailed peer review process (INPO, the Institute of Nuclear Power Operations, and WANO, the World Association of Nuclear Operators) have helped to identify and diffuse best safety practices to the industry.⁸ While the global average capacity factor rose only slowly in the 1990s, to about 82 percent, Belgium, China, Finland, Korea, Mexico, the Netherlands, Romania, Slovenia and Switzerland have achieved factors exceeding 85 percent, with Germany, Sweden, and Hungary at 84 percent.

A second important consideration was the dramatic increase in fossil fuel prices since 2003 and prior to the collapse in prices that has accompanied the ongoing global economic contraction. This increase made both existing nuclear plants and the

⁷ During 2008, spot natural gas prices at Henry Hub, a major gas trading hub, fluctuated between about \$4/MMBtu and about \$14/MMBtu.

⁸ U.S. Energy Information Administration, *Annual Energy Review 2007*, Table 9.1; Nuclear Energy Institute, www.nei.org/keyissues/safetyandsecurity/.

construction of new nuclear plants appear much more economically attractive than was the case prior to 2003. The recent volatility in fossil fuel prices is a related consideration. While the prices for uranium have also been quite volatile during the last year, fuel costs are a much smaller fraction of the total costs for a nuclear plant than for a coal or gas plant. Consequently, the case for building and operating a nuclear plant is much less sensitive to variations in fuel prices than is the case for fossil-fueled generating plants.

A third important consideration relates to emerging climate change policies. The generation of electricity from nuclear plants does not produce CO₂, while coal- and gas-fueled plants do. Coal plants in particular produce about twice as much CO₂ per unit of electricity produced than a CCGT. In a climate change regulatory regime that places constraints on CO₂ emissions, nuclear power becomes more attractive economically compared to fossil-fueled alternatives. As a carbon free source of electricity, nuclear power is being looked at more favorably by some environmental groups than was the case a few years ago.

A fourth consideration that the nuclear industry has promoted with policy-makers is “energy security,” a phrase used to justify many policy initiatives. Unfortunately, exactly what is meant by energy security is rarely articulated very clearly. It typically refers to concerns about dependence on imports of oil from “unstable” areas of the world and the potential effects of large sudden supply disruptions on the economies of oil importing countries. Developed countries, though, use very little oil to generate electricity. In the United States, about 1.2 percent of the electricity generated in 2007 was from petroleum products, and even then, primarily only in relation to the use of capacity

to meet extreme peak demand, for which nuclear power plants are ill suited.⁹ Whatever energy security concerns there may be among oil-importing countries, expanding nuclear generating capacity is not the path to a solution.

These energy security considerations extend as well to natural gas, especially in Europe, with its dependence on supplies of natural gas from or through Russia. These concerns have been heightened by Russia's cutoff of supplies to Ukraine, which adversely affected gas supplies available to other European countries. For most European countries, as well as for Japan, China, and India, additional nuclear capacity would displace the use of natural gas to generate electricity, thereby reducing natural gas imports. In this regard, we note that Finland's decision to build a third nuclear plant at Olkiluoto was influenced, at least in part, by the consideration of natural gas-fueled plants as the benchmark alternative. In contrast, natural gas supplies to U.S. consumers come almost entirely from domestic and (reliable) Canadian sources that sell into an integrated competitive North American market for gas and a fully integrated gas pipeline transportation system.

Finally, in the United States the process for obtaining licenses for building nuclear plants was changed, with the goal of making the process more efficient without sacrificing its effectiveness in assuring safety.¹⁰ These reforms reflect a view that the process that governed the licensing of the current fleet of nuclear plants led to unnecessary delays, uncertainty, and excessive increases in construction costs.

Three of the changes to the process are noteworthy. First, the NRC now certifies specific reactor designs. Once approved, the reactor design can then be used at multiple

⁹ U.S. Energy Information Administration, *Annual Energy Review 2007*, Table 2.1F.

¹⁰ U.S. Nuclear Regulatory Commission, <http://www.nrc.gov/reactors/new-reactors/col.html>.

sites without further design review. The NRC has certified four reactor designs and has four more under review. The NRC now also issues early site permits (ESP) for new reactors. By issuing an ESP, the NRC approves one or more sites for a nuclear power facility, independent of an application for a construction license. The NRC has issued three ESPs and one is pending. Finally, the NRC has consolidated what used to be two separate licensing processes—one to construct a plant and a second to operate it—into a single, combined construction and operating license (COL). By issuing a COL, the NRC authorizes the licensee to construct and (with specified conditions) operate a nuclear power plant at a specific site, in accordance with established laws and regulations. The new COL process is now being tested, as COL applications for 26 new nuclear units have been submitted to the NRC. However, to date none has yet completed the process, and so it is still uncertain whether the new process is able to reduce regulatory delays successfully.¹¹

The changes in the NRC licensing process anticipated the relatively recent increase in interest in building new nuclear power plants in the United States. Accordingly, there was a new licensing process already in place to accommodate the sudden increase in applications for licenses. Countries that do not have such a nuclear plant safety regulatory infrastructure, or that have allowed their regulatory infrastructures to decay as a result of there being, for decades, no applications to build new plants, will have to build or rebuild these infrastructures before new plants can safely move forward.

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¹¹ U.S. Nuclear Regulatory Commission, www.nrc.gov/reactors/new-reactors/design-cert.html, www.nrc.gov/reactors/new-reactors/col.html, and www.nrc.gov/reactors/new-reactors/esp.html.

These changes have implications for both the existing fleet of nuclear plants and for the incentives to build new ones. During the 1990s, nuclear plants in operation began to close, as they were no longer economical to operate on an incremental cost basis. Eleven plants were closed in the United States during this time, however none has closed since 1998.¹² Rather than closing, most of the existing nuclear plants in the United States are expected to seek and receive 20-year extensions on their initial 40-year licenses. As of April 2009, half of the U.S. fleet has received life-extensions from the NRC. Another 20 plants have applied for life-extensions, and 24 have indicated they will apply.¹³ In conjunction with preparing for the life-extension review process, several plants have also invested in new equipment to produce modest increases in generating capacity (“uprating”). In all of these cases, the owners of these plants have justified (to their regulators and their boards) the costs associated with meeting operating and safety requirements to support a 20-year life-extension by demonstrating that the value of the additional electricity produced is greater than the costs incurred.

While policies toward life-extension of the existing fleet of nuclear plants will differ from country to country, we expect that economic and climate change considerations are likely to lead a large fraction of the existing fleet of nuclear plants to continue to operate well beyond the 30- to 40-year lives that were anticipated when they were originally constructed. In France, it is reported, the nuclear operator EDF is likely to continue to seek renewals for existing plants beyond the lives that were anticipated when they were built. Countries like Germany and Sweden, which had planned to phase out nuclear power completely, are now reevaluating those policies.

¹² U.S. Energy Information Administration, *Annual Energy Review 2007*, Table 9.1.

¹³ Nuclear Energy Institute, http://www.nei.org/resourcesandstats/nuclear_statistics/licenserenewal/.

Of course, if nuclear power is limited to the continued operation of the existing fleet of plants, nuclear power's share of electricity generation will fall over time, as electricity demand continues to grow and maximum capacity factor limits are reached (as they have been in the United States and some other countries). Real growth in nuclear power, therefore, is necessarily dependent on the prospects for building new nuclear power plants.

* * *

There are 44 nuclear units under construction globally, with a combined capacity of about 38,000 megawatts, the equivalent of about 10 percent of the generating capacity of the existing global fleet of nuclear plants.¹⁴ Of the 44 plants under construction, 11 are in China, 8 are in Russia, 6 are in India, and 5 are in South Korea. Taiwan, Japan, Ukraine, and Bulgaria each has two plants under construction; Finland, France, and Iran each has one, with a second approved for construction in France. Thus, at present, most construction activity is in developing countries, Russia, or Eastern Europe. As already noted, in the United States 26 applications for licenses for new plants have been filed with the NRC and more are anticipated, though none of these plants is close to commencing construction. The U.K. and Italian governments have indicated that they will adopt policies that will end de facto bans on building new nuclear plants, and interest in acquiring nuclear plants has been expressed by countries in North Africa and the Middle East that currently have no nuclear plants. The IAEA reports that 24 of the 30 countries with nuclear power plants are considering investments in new capacity, and 20

¹⁴ One of these plants is TVA's Watts Bar-2 plant. Construction of the plant began in 1972, was subsequently suspended, and was recently restarted after TVA's apparently successful repowering of Browns Ferry-1.

countries that do not now have nuclear power plants are actively considering developing plants in the future to help to meet their energy needs.

How do the costs of building and operating new nuclear power plants compare to alternative generating technologies, with and without a price on CO₂? How do the primary economic and CO₂-mitigation motivations for building new nuclear power plants weigh against other considerations—safety, energy security, access to nuclear technology to obtain weapons capabilities—that may play a role as well? In attempting to answer these questions, we rely heavily on the 2003 MIT study *The Future of Nuclear Power*, which analyzes the cost of generating electricity from nuclear, coal, and CCGT technologies, as well as other issues associated with commercial nuclear power.¹⁵ The cost analysis has since been updated by Yangbo Du and John Parsons to reflect new construction cost and fuel cost information and to adjust for inflation, and we rely here on this update.¹⁶ While the range of values for some of the input variables is likely to vary from country to country, we believe that these numbers provide a good picture of the relative costs of alternative base-load generating technologies.¹⁷

Because nuclear power plants are much more capital intensive than alternative base-load electric-generating technologies, their economic attractiveness depends heavily

¹⁵ *The Future of Nuclear Power: An Interdisciplinary Study* (Massachusetts Institute of Technology, 2003).

¹⁶ Yangbo Du and John E. Parsons, Update on the Cost of Nuclear Power, Working Paper 09-004 (MIT Center for Energy and Environmental Policy Research, 2009).

¹⁷ Electricity demand varies widely from hour to hour, day to day, and season to season. The difference between the peak and the trough can be a factor of three. Since large volumes of electricity cannot be economically stored, sufficient generating capacity must be built to meet peak demands reliably. Matching supply and demand economically requires a generation portfolio consisting of base load, cycling, and peaking capacity. Base load capacity is designed to operate during the entire year to meet at least the minimum level of demand sustained for a large fraction of the hours of the year. Cycling capacity is designed to meet the incremental demand that is sustained for a smaller fraction of the hours of the year: the additional demand during the day compared to the demand at night. Peaking capacity is designed to operate for a small number of hours each year when demand is at its peak (for example, on the hottest days in the summer). Wind generators, which are even more capital intensive than nuclear plants, do not fall neatly into either of these traditional categories since the quantity of electricity they produce depends on the speed of the wind rather than on the level of demand or the spot price of electricity.

on the construction costs of the plants, the cost of capital (or hurdle rate) used by investors to value the cash flow generated by the plants over time, and the lifetime capacity factor of the plant, since this defines the amount of electricity produced per unit of generating capacity that will earn revenues to cover both the operating and the capital costs of a new nuclear plant. In addition, because nuclear plants do not produce CO₂ emissions, policies that place an explicit or shadow price on CO₂ emissions also affect their economic attractiveness compared to fossil-fueled alternatives.

There has been much confusion and debate about the costs of building new nuclear plants. This situation is largely a consequence of the lack of reliable contemporary data for the actual construction costs of real nuclear plants. Few nuclear plants have been built in the last two decades, and reliable cost information is not typically publicly available. Therefore, any estimate of future construction costs is necessarily uncertain. This is evident from the experience with Olkiluoto Unit 3 in Finland, where construction is running more than two years behind schedule and about 40 percent over initial cost estimates. Much more actual cost information is available for coal-fueled and CCGT plants because there is a significant amount of contemporary experience with building new plants in the United States and Europe. Accordingly, construction cost estimates for new coal and new gas plants are likely to be more reliable.

In addition, construction cost information is also quoted in a number of different ways, making meaningful comparisons both difficult and potentially confusing. Reactor vendors also initially quoted extremely optimistic construction cost numbers for the new generation of nuclear plants that were based on engineering cost estimates rather than real construction experience, and excluded some costs that investors must take into account.

Construction cost estimates should include all costs that are relevant to the potential investor, including not only the costs incurred to build the plant itself, but also the costs of cooling facilities, land acquisition, insurance, fuel inventories, engineering, permitting, and training.

For cost comparisons to be meaningful they must be based on a common computational format. The standard cost metric used for evaluating the costs of electric-generating plant alternatives is the “overnight cost” of building the plant. This is the cost of building the plant as if it could be built “instantly,” that is, using current prices and without the addition of finance charges related to the time required for construction. These costs, as well as differences in cash flow profiles during construction and plant life, are not ignored, but are handled separately in the evaluation of the cash flows required to pay back the total costs of alternative generating technologies once the overnight construction cost estimates are determined. The reason for working with overnight costs rather than just adding up the construction cost dollars expended is to be able to account for different construction periods, rates of inflation, and costs of capital that may be attributed to different technologies, and to express cost comparisons at the same general price levels.

The capacity factor assumed also has important implications for the unit cost that is derived. If the capacity factor is low, then the total cost per unit of electricity produced will be high, since the capital and fixed operating costs must be covered by fewer units of production, and vice versa. The capacity factor of U.S. nuclear power plants today is about 90 percent, and some analyses of nuclear power costs assume that new plants will immediately operate at 90 percent or higher capacity factors. However, while the capacity

factors of the existing fleet of U.S. plants today is about 90 percent, their lifetime capacity factor is less than 80 percent. And it is the *lifetime* capacity factor that is relevant for evaluating the costs of an investment in a new plant, since they must recover their investment from the output produced by the plant over its economic lifetime. Globally, lifetime capacity factors were about 82 percent as of 2007, remaining roughly constant since 2000. Only Finland has a fleet of nuclear plants with lifetime capacity factors greater than 90 percent, and only four other countries have fleets with lifetime capacity factors greater than 85 percent. Two recently completed plants in South Korea reached 90 percent capacity factors quickly, but another two had not achieved lifetime capacity factors of 90 percent after six years of operation. Three of the four most recently completed plants in Japan have a lifetime capacity factor of less than 70 percent, and the fourth has a factor less than 80 percent. Low capacity factors in the early years of plant operation are especially burdensome to the economic attractiveness of investment in a nuclear plant since the revenue stream is present valued to evaluate the investment, and weights are larger on early years than on distant years. Overall, we consider the assumption that new plants will operate at 90 percent capacity factors almost as soon as they are completed to be very optimistic.

Table 1 displays our estimates of the costs of generating a kWh of electricity for base-load nuclear, coal, and CCGT generating technologies. These cost estimates are updates of the ones contained in the MIT study *The Future of Nuclear Power*, to reflect more recent information, real changes in construction costs, and general inflation. The table shows the capital cost for the three technologies, expressed as an overnight cost per unit of capacity. The overnight cost for construction of a new nuclear power plant is

\$4,000 per kilowatt of capacity, measured in 2007 dollars. The overnight cost for a coal plant is \$2,300/kW, and \$850/kW for a CCGT plant. The table also shows the fuel cost for each of the three technologies. The cost of uranium, together with all of the costs for enrichment and fabrication, yields a total fuel cost for nuclear power of \$0.67/MMBtu. Because the prices of coal and natural gas are so volatile, and because these can represent a substantial fraction of the cost of producing electricity, we show the cost of electricity under three scenarios for the prices of coal and gas. The moderate coal-price scenario assumes a delivered price of coal of \$65/ton, which translates to \$2.60/MMBtu, assuming that this is a Central Appalachian coal with 12,500 Btu. The low coal-price scenario is \$40/ton, or \$1.60/MMBtu, and the high scenario is \$90/ton, or \$3.60/MMBtu. The moderate natural gas-price scenario is \$7.00/MMBtu; the low scenario is \$4.00/MMBtu; and the high scenario is \$10.00/MMBtu.

The last column of Table 1 shows the calculated cost of electricity for each of the three technologies. This is the price that a generator would have to charge, escalated with inflation, in order to cover its fuel and other operating costs, and to earn a return on its capital equal to the opportunity cost of capital invested in the plant. The required return on capital will depend upon the many institutional arrangements of the electric power industry. Plants may be built either by public authorities or by private companies, and private companies may operate as public utilities under rate-of-return regulation, or may operate under the “merchant model” in which they construct plants at their own risk, earning profits from the sale of the power into competitive wholesale markets. The costs of electricity we show in Table 1 are based on the cost of capital required by private investors operating within this “merchant model.” Because of the past poor record of

construction of nuclear power plants, because of the enormous uncertainty surrounding the estimated cost of construction of a new nuclear power plant, and because of the uncertainty surrounding the success of the new combined construction and operating license process, *The Future of Nuclear Power* applied a slightly higher cost of capital to nuclear power than to coal- or gas-fired power; the cost update does so as well. A major task facing the U.S. nuclear industry, including the NRC, is proving that construction costs and the risk of delays and overruns have been reduced. Doing so would reduce the required cost of capital and bring down the cost of electricity from nuclear power. The costs shown in Table 1 do not incorporate the benefits of loan guarantees or production tax credits offered under the Energy Policy Act of 2005.

The updated cost of electricity from nuclear power is 8.4¢/kWh. This is higher than the 6.2¢/kWh for coal and the 6.5¢/kWh for gas under our moderate coal- and gas-price scenarios. Under our high coal- and gas-price scenarios, the cost of electricity from coal is 7.2¢/kWh, which remains below that from nuclear, while the cost of electricity from natural gas is 8.7¢/kWh, which is above that from nuclear. The capital cost represents nearly 80 percent of the cost of electricity produced by nuclear power, but only 15 percent of the cost of electricity produced by gas, with coal being an intermediate case. Fuel cost represents approximately 80 percent of the cost of electricity produced by gas, but only 10 percent of the cost of electricity produced by nuclear, with coal again being an intermediate case.

Table 2 displays the same updated numbers but adds a charge for CO₂ emissions. Two levels are considered: \$25/tonne of CO₂ and \$50/tonne of CO₂. It is unlikely that large-scale carbon capture and sequestration (CCS) investments would be economical at

these levels, so investment in coal with CCS is not an economical substitute at these CO₂ price levels. Even at the lower charge of \$25/tonne of CO₂, the cost of power from coal in our moderate coal-price scenario is up to 8.3¢/kWh so that nuclear would be competitive with coal. At the higher charge of \$50/tonne of CO₂, nuclear power is cheaper than coal even at the low coal-price scenario. At the lower charge of \$25/tonne of CO₂, the cost of power from gas is still less than the cost from nuclear in both the low and the moderate gas-price scenarios. At the higher charge of \$50/tonne of CO₂, nuclear power is cheaper than gas in both the moderate and high gas-price scenarios, although not in the low gas-price scenario.

These numbers illustrate the tradeoffs facing an investor making a choice on which type of capacity to install. For nuclear power, the main source of uncertainty is at the point of construction. For coal-fired power, the price of coal matters; but the choice society makes about the penalty for carbon emissions is the central driver and risk. For gas-fired power, both the price of natural gas and the charge for carbon are major risks.

* * *

Of course, the future of nuclear power will depend on more than conventional economic considerations. In this section, we briefly discuss the most important of those other considerations, though we do not think that the passage of time since its publication in 2003 has changed the conclusions regarding these considerations that can be found in *The Future of Nuclear Power*.

It is imperative that all nuclear facilities—reactors as well as enrichment, fuel storage, and reprocessing facilities—be operated with high levels of safety. While many of the safety metrics for existing reactors have improved significantly in recent years, *The*

Future of Nuclear Power argues that the probability of a serious accident remains too high to support a large expansion in the fleet of nuclear plants. We subscribe to that study's recommendations for improving safety in both the short run and the long run. Unless nuclear reactors and the nuclear fuel cycle are perceived virtually to guarantee that there will not be a major accidental release of radioactive materials that would have significant adverse effects on human health and welfare, public support for nuclear power will erode quickly, as it did after the incidents at Three Mile Island and Chernobyl. Moreover, it is important that high safety standards be established and enforced internationally, as an accident in one country can have both direct adverse health and welfare effects on neighboring countries and indirect adverse effects on public acceptance of nuclear power in all countries.

A continuing challenge is the deployment of long-term storage or disposal facilities for the high-level radioactive waste produced by nuclear power plants and fuel-cycle facilities. No long-term spent-fuel storage or disposal facilities are yet in operation. The programs in Finland, Sweden, France, and the United States are the most advanced, though funding for the waste disposal facility planned for Yucca Mountain in Nevada was recently canceled. From a safety perspective, it is not necessary to solve the long-term problem now. Waste fuel can be stored in dry casks in secure facilities for 50 years or more and await further technological, economic, and political developments. However, the absence of a long-term strategy for waste does create potential political problems, and some countries may not proceed with nuclear power until this challenge is resolved.

The expansion of nuclear power must be accompanied by safeguards to assure that it does not lead to the proliferation of traditional nuclear weapons or increase access

to highly radioactive materials that could be used in so-called dirty bombs, which use conventional explosives to diffuse these materials widely in an urban area, with potential adverse effects on human health as well as causing costly disruptions in normal commercial and other human activity. The pathways to weapons proliferation arising from the expansion of nuclear power are access to enrichment and reprocessing technology, and ready access to or theft of stocks of reprocessed plutonium or highly enriched uranium. The risks related to diversion of plutonium are potentially higher if reprocessing and recycling of spent fuel is widely adopted. Reactor and fuel-cycle security protocols that can reduce unauthorized access to materials that could be used to create dirty bombs, and the detection of such devices, need more attention at an international level.

The Future of Nuclear Power makes several useful recommendations regarding weapons proliferation. (It does not make policy recommendations related to dirty bombs.) They include (a) strengthening the IAEA's safeguard functions and expanding its authority to inspect suspected illicit facilities; (b) giving greater attention to proliferation risks from enrichment technologies; (c) moving IAEA safeguards to a model built around continuous material protection, control, and accounting, both in facilities and in the transportation of nuclear materials; (d) focusing fuel-cycle research and development on minimizing proliferation risks; and (e) moving forward quickly with agreements to create secure international spent-fuel storage facilities. These continue to be wise recommendations. In addition, efforts to dissuade countries from acquiring enrichment, fuel fabrication, and reprocessing facilities, by creating and providing credible long-term

commercial access to international stockpiles of low-enriched uranium nuclear fuel, are also worthy of continuing support.

Our analysis so far has focused on the economic attributes of continued operation and investment in the currently available generation of existing and new light water reactors using an open fuel cycle with low-enriched uranium fuel. We have focused on this reactor/fuel-cycle combination because it continues to appear to represent the lowest cost option for existing and new nuclear power plants at present. Today, the primary alternative to an open fuel cycle using low-enriched uranium is a closed fuel cycle that reprocesses spent fuel by chemically separating the plutonium and depleted uranium from the fission products and minor transuranic elements in the spent fuel (the PUREX–Plutonium-Uranium Extraction–process) and then fabricating a Mixed Oxide (MOX) fuel composed of both plutonium and uranium for “recycling” as reactor fuel in light water reactors. Although the United States originally developed the PUREX process to recover plutonium for use in nuclear weapons, U.S. policy for over three decades has banned exports of reprocessing technology and the use of recycled plutonium in civilian reactors. However, the United States has continued research and development on reprocessing technology, and there continues to be some political and commercial support for lifting the ban on reprocessing and the use of recycled plutonium in reactor fuel used in U.S. reactors. France, Japan, the United Kingdom, Russia, India, and China have and use reprocessing technology, or use MOX fuel produced in other countries.

Most studies conclude that reprocessing spent fuel and fabricating MOX fuel is more costly than using fresh low-enriched uranium.¹⁸ At best, the costs of the open and

¹⁸ *The Future of Nuclear Power*; Matthew Bunn, Steven Fetter, John P. Holdren and Bob van der Zwaan, 2003, “The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel,” Harvard Kennedy

closed fuel cycles are close to a wash today and over the next few decades. The economic calculus could change if uranium prices were to increase significantly and/or the costs of reprocessing and fuel fabrication were to fall significantly. As we have already indicated, fuel costs are a relatively small fraction of the total costs of new nuclear power plants. Accordingly, the basic economics of nuclear power vis-à-vis alternative fossil-fuel technologies are unlikely to turn on a decision to reprocess and recycle spent reactor fuel or not. Rather, the decision to reprocess and recycle is more likely to be driven by other concerns. Recycling via MOX has no obvious waste disposal benefits, and there is significant concern about the danger of the potential diversion of separated plutonium to make nuclear weapons.

* * *

In those countries that have been able to improve the performance of their existing fleet of nuclear plants it will typically be economical to extend their operating lives well beyond 40 years given reasonable forecasts of fossil fuel prices. Imposing explicit or implicit prices on CO₂ emissions makes the economics of life extensions even more compelling. The primary barriers to life-extension of the existing fleet of light water reactors are managerial capabilities to operate the plants safely and at high capacity factors, political pressures to close nuclear plants quickly for reasons other than economics, and regulatory constraints that increase the costs of meeting life-extension criteria.

Of course, merely extending the lives of existing nuclear plants will not constitute a nuclear “renaissance.” In this case, nuclear’s contribution to the electricity supply will

simply shrink over a longer period of time. To stimulate a true nuclear renaissance that leads to significant investments in new nuclear plants, several changes from the status quo will need to take place: (a) a significant price must be placed on CO₂ emissions, (b) construction and financing costs for nuclear plants must be reduced or at least stabilized, and the credibility of current cost estimates verified with actual construction experience, (c) the licensing and safety regulatory frameworks must demonstrate that they are both effective and efficient, (d) fossil fuel prices need to stabilize at levels in the moderate to high ranges used in Tables 1 and 2, and (e) progress must be made on safety and long-term waste disposal to gain sufficient public acceptance to reduce political barriers to new plant investments.

Absent the imposition of explicit or implicit prices on CO₂ emissions, and given the current expected costs of building and operating alternative generating technologies, it does not appear that a large nuclear renaissance will occur based primarily on the economic competitiveness of new nuclear power plants compared to alternative fossil-fueled base-load generating technologies. It does not appear that new nuclear power plants would be a competitive base-load generating alternative to conventional supercritical coal-fueled technology, even with high coal prices. New nuclear plants are competitive with natural gas-fueled CCGT technology only at very high gas prices. The imposition of significant prices on CO₂ emissions makes nuclear competitive with coal-fueled generating technology under all fuel price scenarios, and with gas-fueled CCGT technology when gas prices are at moderate or high levels. A high CO₂ price makes CCGT technology very competitive with coal-fueled generating technology at all fossil-fuel price levels. Thus, with significant CO₂ prices, economic considerations would lead

to a shift to gas from coal for new fossil plants, increasing the demand for and price of natural gas to the moderate to high levels. This suggests that with significant CO₂ prices, economic considerations alone would lead to a mix of new nuclear and new CCGT plants with gas prices at moderate to high levels. The higher is the equilibrium gas-price trajectory, the larger would be the share of new nuclear plants.

The economic attractiveness of nuclear power could also be improved if the costs of building and financing nuclear plants could be reduced from the levels indicated by the available information on construction and financing costs that we have relied upon here. It is possible that as new nuclear plants are built around the world, their construction costs will decline significantly as construction experience accumulates. This possibility is one of the rationales for the financial incentives contained in the Energy Policy Act of 2005. Construction costs would have to decline on the order of 20 percent to make nuclear competitive with coal, in the absence of significant CO₂ charges. Financing costs could also be reduced below those assumed here for plants built under supportive cost-of-service regulatory regimes (as in Florida) or as a result of government policies, such as the government loan guarantees provided for in the Energy Policy Act of 2005.

Another consideration is uncertainty about construction costs and capacity factors. We have reasonably good information about the actual costs of building and operating new coal and CCGT plants since many have been built and placed into operation around the world in the last decade. The quality of the construction cost information for new nuclear plants is not nearly as good since there are so few recently constructed plants for which credible construction cost data are available. Du and Parsons' estimates rely on a mix of actual construction cost data and estimates of construction costs found in recent

regulatory filings. In addition, the human and manufacturing infrastructure required to produce major nuclear plant components, perform detailed engineering, and construct new nuclear plants has deteriorated significantly in the past decades. This means that a surge in nuclear plant orders will run up against capacity constraints on the supply of key components and labor, leading to higher component manufacturing costs and higher construction costs, until these infrastructures can be rebuilt to support renewed investment in new nuclear generating capacity. The early-life capacity factors of new nuclear plants also vary fairly widely, and the *expected* capacity factor for a new plant during a “break-in” period may be significantly less than the more than 90 percent assumed in more optimistic assessments.

There are other, more difficult-to-quantify barriers to a large deployment of new nuclear power plants. The new licensing system in the United States is untested, and licensing systems in many countries with nuclear plants have not yet been reconfigured to accommodate applications for new plants. Countries without nuclear power must develop and implement regulatory frameworks to license new plants and to ensure that they operate safely. The challenges of developing an effective licensing and safety regulatory framework from scratch have not been fully recognized by those countries considering nuclear power plants for the first time. The Energy Policy Act of 2005 provides financial incentives (in the form of insurance against the costs of regulatory delays) for the first few plants to go through the new U.S. regulatory system, in recognition of the costs that may be imposed on the first few license applicants as the new regulatory framework is fully road tested. We are not aware of similar policies in other countries.

Finally, political constraints driven by concerns about safety, long-term waste disposal, and proliferation may further deter some countries from launching major new nuclear power programs. Another significant accident at an existing nuclear plant anywhere in the world could have very negative consequences for any hope of a nuclear renaissance.

All things considered, the best economic case supporting a significant expansion in nuclear power capacity involves significant CO₂ emissions charges, moderate to high fossil fuel prices (including implicit prices reflecting energy security considerations), declining nuclear plant construction costs, and an efficient licensing regulatory framework

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Table 1: Costs of Electric Generation Alternatives

	Overnight Cost	Fuel Cost	Levelized Cost of Electricity
	\$/kW	\$/MMBtu	¢/kWh
Nuclear	4,000	0.67	8.4
Coal (low)	2,300	1.60	5.2
Coal (moderate)	2,300	2.60	6.2
Coal (high)	2,300	3.60	7.2
Gas (low)	850	4.00	4.2
Gas (moderate)	850	7.00	6.5
Gas (high)	850	10.00	8.7

Notes: The low, moderate, and high fuel costs for coal correspond to a \$40, \$65, and \$90/short ton delivered price of Central Appalachian coal (12,500 Btu), respectively. Costs are measured in 2007 dollars.

Table 2: Costs of Electric Generation Alternatives, Inclusive of Carbon Charge

	Overnight Cost	Fuel Cost	Levelized Cost of Electricity	
			w/carbon charge	w/carbon charge
			\$25/tCO ₂	\$50/tCO ₂
	\$/kW	\$/MMBtu	¢/kWh	¢/kWh
Nuclear	4,000	0.67	8.4	8.4
Coal (low)	2,300	1.60	7.3	9.4
Coal (moderate)	2,300	2.60	8.3	10.4
Coal (high)	2,300	3.60	9.3	11.4
Gas (low)	850	4.00	5.1	6.0
Gas (moderate)	850	7.00	7.4	8.3
Gas (high)	850	10.00	9.6	10.5