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NUCLEAR ENERGY

Rebirth or Resuscitation?

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Nuclear Energy: Rebirth or Resuscitation?

Sharon Squassoni

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SUMMARY

After several decades of disappointing growth, nuclear energy seems poised for a comeback. Talk of a "nuclear renaissance" includes perhaps a doubling or tripling of nuclear capacity by 2050, spreading nuclear power to new markets in the Middle East and Southeast Asia, and developing new kinds of reactors and fuel-reprocessing techniques. But the reality of nuclear energy's future is more complicated. Without major changes in government policies and aggressive financial support, nuclear power is actually likely to account for a *declining* percentage of global electricity generation.

Projections for growth assume that government support will compensate for nuclear power's market liabilities and that perennial issues such as waste, safety, and proliferation will not be serious hurdles. Before embarking on such a path, policy makers need to achieve greater certainty across a wide range of issues. In the meantime, all possible efforts should be made to minimize the risks of any nuclear expansion that might occur. These include strengthening the rules of nuclear commerce and transparency, deemphasizing the element of national prestige with respect to nuclear energy, undertaking clear-eyed assessments of all available options for generating electricity, and limiting the acquisition of sensitive nuclear technologies like uranium enrichment and spent-fuel reprocessing.

NUCLEAR ENERGY:
REBIRTH OR RESUSCITATION?

Enthusiasm for nuclear energy is on the rise worldwide. After two decades of disappointing growth, industry leaders are forecasting a nuclear renaissance. Predictions of a "nuclear renaissance" envision a doubling or tripling of nuclear capacity by 2050, spreading nuclear power to new markets in the Middle East and Southeast Asia, and developing new kinds of reactors and fuel-reprocessing techniques. During the presidency of George W. Bush, the United States promoted nuclear energy both at home and abroad. Programs like the 2006 Global Nuclear Energy Partnership and President Bush's 2007 joint declaration with then–Russian president Vladimir Putin to facilitate and support nuclear energy in developing countries have helped underwrite the notion of a major worldwide nuclear revival.

Renewed interest in nuclear energy arises from the desire to find alternatives to expensive oil and natural gas as well as the perception of nuclear energy as a readily deployable option for making the rapid and dramatic reductions in carbon dioxide emissions necessary to mitigate climate change. Energy security and climate change are invariably mentioned as the top two reasons for pursuing nuclear energy today.

A major expansion of nuclear power, however, is not a foregone conclusion. The traditional challenges besetting nuclear energy—cost, safety, waste, and proliferation—continue to limit widespread growth. Government policies supporting nuclear energy would be necessary to make major expansion a reality. In considering whether or not to promote nuclear energy, a starting point for analysis is whether nuclear energy can really make a significant difference for energy security and for climate change mitigation.

This report suggests that nuclear power could provide greater diversity of electricity resources, but will not solve the dilemma of dependence on foreign oil. Moreover, few countries can expect more than *interdependence* when it comes to nuclear energy because of the existing nuclear supply structure and location of uranium resources.

Nor is nuclear power going to make a big difference in reducing carbon emissions in the next two decades, when the biggest reductions will have the most impact. Nuclear power is certainly a cleaner alternative to coal-based electricity, but the need for dramatic and immediate reductions in carbon emissions suggests cheaper and quicker approaches that span all energy uses, not just electricity—namely, improved efficiency. This report specifically examines the nuclear industry's capacity to build enough reactors to reduce carbon emissions significantly in the next two decades.

The current enthusiasm about nuclear energy as a major solution to climate change and energy insecurity obscures the challenges that nuclear energy has not yet overcome. The economic competitiveness of new nuclear reactors is subject to debate, although imposing carbon pricing may enhance nuclear energy's marketability. The current financial crisis will undoubtedly make it tougher to finance new nuclear power plants. Though new reactor designs now incorporate better safety features, deploying new reactors in as many as thirty additional countries will present particular challenges, as will extending the lives of aging reactors still in operation.

Nuclear waste disposal is still highly controversial. The United States, with the world's largest number of nuclear reactors, has not yet solved the issue of long-term waste disposal, and neither has any other country. And the proliferation risks of nuclear power, posed by no other source of electricity, are likely to grow with major nuclear expansion. In addition to expanding nuclear expertise generally in politically volatile regions, the potential spread of uranium enrichment and spent-fuel reprocessing capabilities and plutonium-fueled reactors to additional countries could strain the current system for inspecting nuclear material and facilities. If demand for nuclear energy exceeds supply, aspiring nations might be tempted to take shortcuts in developing the infrastructure needed to maximize safety and security. Alternatively, a new tier of nuclear suppliers could emerge to meet demand, with potentially negative safety, security, and proliferation effects.

For these reasons, it is imperative to approach any potential nuclear expansion with an eye toward minimizing risks. The first step would be to ensure that states are choosing nuclear energy because it makes sense as a way to produce electricity, rather than as a path to national status. Another key step would be to strip away the prestige associated with national uranium enrichment facilities. This could be done in the context of negotiating a fissile material production cutoff treaty that would gradually phase out national uranium enrichment facilities. Other measures would include reactor vendors adopting the International Atomic Energy Agency's (IAEA) strengthened safeguards protocol as a condition of supply, through both commercial channels and through the Nuclear Suppliers Group, enhancing the transparency of peaceful nuclear cooperation agreements, and placing priority within the Global Nuclear Energy Partnership on commercializing small and proliferation-resistant reactors. The exigencies of energy security and climate change do not warrant racing ahead before institutional frameworks can ensure that any expansion makes sense, not just for energy needs, but for world security.

THE "NUCLEAR RENAISSANCE"

The much-heralded "nuclear renaissance" is, in many ways, a misleading description of what is happening in the global nuclear energy industry today. International assessments project that without major changes in government policies and aggressive financial support, nuclear power is actually likely to account for a *declining* percentage of global electricity generation. For example, the International Energy Agency's (IEA's) *World Energy Outlook 2008* projects that without policy changes, nuclear power's share of worldwide electricity generation will drop from 15 percent in 2006 to 10 percent in 2030.

The term "renaissance" might most aptly be used for the United States, where the prospect of building any new reactors is considered quite positive because no nuclear reactors have been licensed in about thirty years. Since 2007, fifteen applications for twenty-four new power plants have been submitted. Proponents hope that as many as thirty to forty-five new reactors could be operational by 2030.

Abroad, the biggest push for nuclear power plants will come in Asia. Japan and South Korea have been steadily adding nuclear power plants, but major growth is expected in China and India, because each hopes to add scores of reactors in the next two decades. In Europe, Italy is reconsidering nuclear energy, and rumors circulate that countries such as Germany and Sweden might delay or abandon phasing out nuclear power to meet climate change goals. Other countries (such as Canada, South Africa, and South Korea) plan to expand their programs to include uranium enrichment, plutonium reprocessing, or both.

But that fact that more than two dozen additional states are also interested in nuclear power is perhaps the most notable element of the "nuclear renaissance." Half of these are developing countries. Some—

like Turkey, the Philippines, and Egypt—have abandoned nuclear programs in the past, while others—like Jordan and the United Arab Emirates—are considering nuclear power for the first time. If all these states follow through on their plans, the number of states with nuclear reactors could double.

Record-high oil and natural gas prices and a widespread realization that the world must shift from carbon-based energy are two driving motivations for renewed interest in nuclear energy. Yet a careful look at energy security and global climate change raises questions about the relevance and viability of nuclear power as a way to meet these challenges.

ENERGY SECURITY AND NUCLEAR POWER

Energy is the lifeblood of industrial economies and the key to advancement for developing countries.[1] Secure energy is a matter of reliable, adequate, and affordable supply.[2] As the prices of oil and natural gas have risen, so too have concerns about energy security. Higher oil and gas prices have not only been painful for many economies, but a spate of price disputes has also brought the vulnerability of supply into sharp relief. Price disputes between Russia and Ukraine resulted

1. John Turner of the U.S. National Renewable Energy Laboratory suggested that energy is as important as food and water to modern society and that "securing our energy future is critical for the viability of our society." Quoted by Sandi Schwartz, Tima Masciangioli, and Boonchai Boonyaratanakornkit, *Bioinspired Chemistry for Energy*, Workshop Summary to the Chemical Sciences Roundtable (Washington, D.C.: National Research Council of the National Academies, 2008), 3.

2. This is the definition used by the International Energy Agency, *World Energy Outlook 2007* (Paris: International Energy Agency, 2007), chap. 4, on world energy security. Daniel Yergin suggested that though the developed world defines energy security usually as the "availability of sufficient supplies at affordable prices," other states' definitions vary according to whether they export energy (Russia), how well they can adjust to dependence on global markets (China, India), diversification, and investment in overseas resources (Japan). Daniel Yergin, "Ensuring Energy Security," *Foreign Affairs* 85, no. 2 (March–April 2006), 69–82. More elaborate definitions, such as that of A. F. Alhajji, incorporate notions of economic growth: "Energy security is the steady availability of energy supplies that ensures economic growth in both consuming and producing countries with the lowest social cost and lowest price volatility." Quoted by Robert Bryce, *Gusher of Lies: The Dangerous Delusions of Energy Independence* (New York: Public Affairs, 2008), 267. On the reliability of electricity supply, also see the definitions used by the International Energy Agency, *World Energy Outlook 2007*, 161.

in temporary cutoffs of natural gas to Western and Central Europe in 2006 and 2008. In 2007, Russia halted oil supplies to Azerbaijan, Germany, Poland, and Slovakia. There have been other sources of temporary cutoffs as well. In 2006, severe weather, technical glitches, political instability, and nationalization efforts all contributed to temporary production shutdowns of oil and gas from the Gulf of Mexico, the Trans-Alaskan Pipeline, and from Nigeria and Bolivia.

Nuclear power is increasingly seen as a way to reduce dependence on foreign oil and natural gas, to combat rising energy costs, and to achieve ever-elusive "energy independence." For example, in a speech on May 27, 2008, Senator John McCain stated that "civilian nuclear power provides a way for the United States and other responsible countries to achieve energy independence and reduce our dependence on foreign oil and gas." This echoes President Bush's statements in February and March 2007 that "if you really do want to become less dependent on foreign sources of energy and want to worry about the environment, there's no better way to protect the environment than the renewable source of energy called nuclear power" and that "nuclear power plants emit zero greenhouse gases. It doesn't require any hydrocarbons from overseas to run those plants."

However, most countries will not be able to reduce their dependence on oil by building nuclear power plants. Nuclear energy—because it currently only produces electricity—is inherently limited in its ability to reduce this dependence. Oil and natural gas are consumed in much larger proportions in industry and transportation, and for residential and commercial heating (see the example of the United States in figure 1). In the United States, 40 percent of the energy consumed comes from oil, yet oil produces only 1.6 percent of electricity. As figure 1 shows, natural gas usage in the United States is split almost evenly among industrial uses, residential and commercial heating, and electricity generation.

In most countries, oil is used sparingly for electricity because it is expensive and is reserved to provide extra capacity (so-called peak load) when electricity demand is highest.[3] Globally, oil is expected to decline from providing about 7 percent now of power generation to 3 percent by 2030.[4] Only in the Middle East does oil still account for

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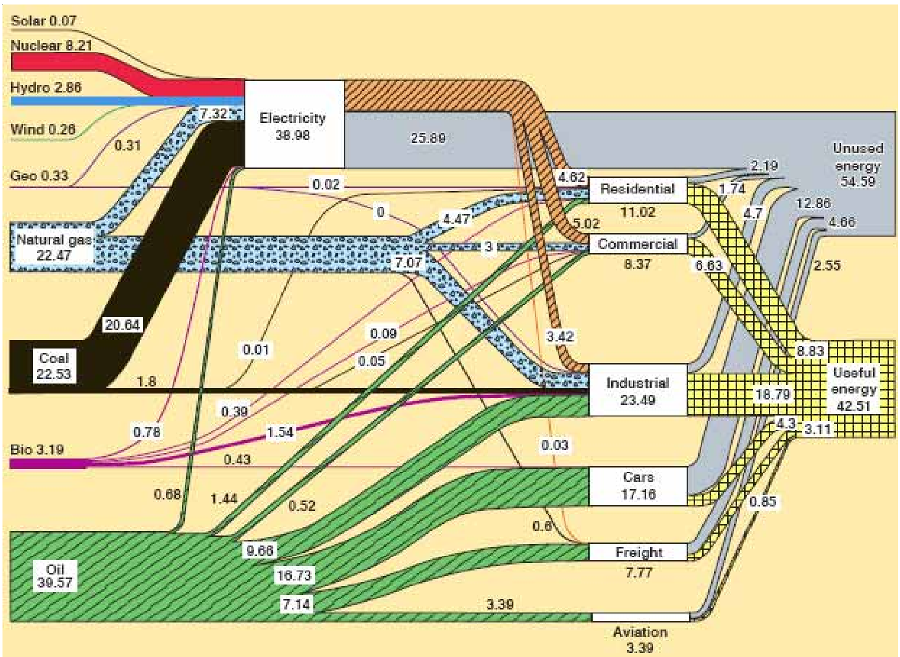
3. Italy, which still uses oil to generate 26 percent of its electricity, is somewhat of an anomaly in Western Europe, which may be why it is reconsidering nuclear energy.

4. International Energy Agency, *World Energy Outlook 2007*, 93.

FIGURE 1
Estimated Energy Usage in the United States 2006 ~97.1 Quads



Source: Lawrence Livermore National Laboratory, 2008; the data are based on "Annual Energy Review 2006: June 2007," DOE/EIA-0384 (2006), U.S. Department of Energy. Note: 1 quad = 1 quadrillion British thermal units.

substantial electricity generation—about a third of the total.[5] In all, this means that nuclear electricity could only substitute for a very small amount of imported oil worldwide.

Countries that have turned to nuclear power to reduce their dependence on foreign oil have largely been unsuccessful. After the 1970s oil shocks, France and Japan embarked on major nuclear construction. Although France reduced its reliance on oil for electricity tenfold (from 10 percent in 1973 to 1.5 percent in 1985), oil as a percentage of total energy consumption started to climb again after 1985. French officials maintain that "France's energy independence, higher than 50 percent, has more than doubled" over the last twenty-five years, but the reality

5. McClatchy News Service, "Vicious Cycle: Middle East Affluence Drive Up M.E. Oil Use and Price," April 18, 2008, accessed at www.energyinvestmentstrategies.com.

is far more complex.[6] France would need to wean itself from the use of oil in the transportation sector to truly reduce its dependence on foreign sources.

Likewise, Japan has diversified its energy sources to include nuclear power, natural gas, and coal, but it still depends on imports for 96 percent of its primary energy supply.[7] This is the case even though it only uses oil for 6 percent of its power output, compared with 36 percent of its nuclear power output.[8] Oil still accounts for about half of its primary energy supply, and nearly 90 percent of its imported oil comes from the Middle East.[9]

The widespread deployment of plug-in hybrid electric vehicles could change the equation for a trade-off between nuclear energy and oil. But such a widespread deployment would also change the equation for all sources of electricity, including intermittent sources like wind and solar power. According to some experts, such plug-in cars could serve as electricity storage for intermittent sources, creating a symbiotic relationship. In any event, it would take at least two decades to switch over the estimated 900 million vehicles on the road from oil to electricity.[10] Until then, nuclear energy cannot reduce this heavy reliance on oil.

The case is different for natural gas. Although natural gas also has industrial and heating uses, it accounts for about one-fifth of electricity production worldwide. Natural gas is an attractive way to produce electricity because, according to the IEA, "gas-fired generating plants are very efficient in converting primary energy into electricity and cheap

6. Mycle Schneider, "Nuclear Power in France: Systemic Issues Influencing Costs," draft, commissioned by the Nonproliferation Policy Education Center, March 2008.

7. This figure drops to 81 percent if domestic nuclear energy is included. For comparison purposes, Italy's dependence on foreign energy imports is 85 percent; Germany's is 73 percent (dropping to 61 percent if nuclear is included); France's is 93 percent (dropping to 50 percent if nuclear is included), and the United States' is 39 percent (dropping to 30.3 percent if nuclear is included). See http://www.fepc.or.jp/english/energy_electricity/supply_situation/index.html, which draws on IEA, "Energy Balances of OECD Countries, 2004–2005."

8. The difference between generating capacity and actual output is basically the difference between potential and actual supply.

9. See http://www.fepc.or.jp/english/energy_electricity/supply_situation/index.html.

10. The first hybrid car was produced in 1899 by Lohner-Porsche, but commercialization is just beginning. Key issues include the cost, weight, and technology of batteries. According to the IEA, there are about 900 million vehicles on the road today, and this number is expected to exceed 2.1 billion by 2030. The average turnover of fleets of light vehicles is about fifteen years.

to build, compared with coal-based and nuclear power technologies."[11] Nuclear energy could displace natural gas for electricity production and improve some countries' stability of energy supply.

Concerns About Foreign Dependence

Uranium—the feedstock of nuclear energy—is easy to transport and stockpile, and therefore much less vulnerable to supply disturbances than natural gas. Most uranium is purchased using long-term contracts, making it less susceptible also to price fluctuations. Uranium resources exist around the globe, another advantage from an energy security perspective. Stable suppliers like Australia and Canada account for more than half of current production and more than 90 percent of known reserves. States without nuclear power hold at least 40 percent of the world's uranium reserves—Australia and Kazakhstan (see table 1). Countries such as France, Germany, Japan, and South Korea, with little or no uranium of their own, have successfully relied on uranium imports for many years.

The location of uranium is not the only source of foreign dependence on nuclear power. Uranium requires considerable processing before it can be used as fuel. After mining and milling, three steps are necessary to turn uranium into fuel: conversion into a form suitable for processing, enrichment (to raise the percentage of the fissile isotope U-235 above the less than 1 percent found in natural uranium), and fabrication into fuel.[12] The market has consolidated over the years, and in each of these fuel production steps, four suppliers account for more than 80 percent of the market.[13]

Likewise, the number of reactor vendors has shrunk in the last twenty years, as figure 2 shows. A few of these, like the vertically integrated French (AREVA) and Russian (Atomenergoproject) organizations, can offer one-stop nuclear shopping. The majority of states

11. International Energy Agency, *World Energy Outlook 2007*, 86.

12. About 90 percent of the reactors currently operating worldwide are so-called light-water reactors, which use water to cool and moderate the reactor and low-enriched uranium fuel. Other designs, such as pressurized heavy-water reactors that do not require enriched uranium fuel, are deployed in smaller numbers.

13. Four companies in Russia, France, the United States, and Canada account for 88 percent of the uranium conversion market. Four major enrichment corporations account for 95 percent of the market (Tenex, Eurodif, Urenco, and the U.S. Enrichment Corporation). And four companies account for 84 percent of the fuel fabrication market (AREVA, Westinghouse, Global Nuclear Fuel, and TVEL) of a total of sixteen suppliers in eighteen countries.

TABLE 1
Uranium Resources in Selected International Atomic Energy Agency Member States

Country	Uranium Resources (Tons Uranium) RAR (<US $130/kilograms Uranium)	Percentage of World Resource (%)	No. of Nuclear Power Reactors (% Electricity)
Countries with major uranium resources but without nuclear power reactors			
Australia (second largest producer of uranium)	735 000	23.0	None
Kazakhstan	530 460	17.0	None
Namibia	170 532	5.0	None
Niger	102 227	3.0	None
Uzbekistan	79 620	2.5	None
Mongolia	46 200	1.5	None
Countries with uranium resources and nuclear power reactors			
USA	345 000	11.0	104 (20)
Canada (largest producer of uranium)	333 834	10.5	20 (~12)
South Africa	315 330	10.0	2 (5.9)
Russian Fed.	143 020	4.5	30 (16)
Brazil	86 190	3.0	2 (4)
China	35 060	1.1	9 (1.4)
India*	40 980	1.3	15 (~3)
Countries with many nuclear power reactors but without significant uranium resources			
France	No domestic		59 (78)
Germany	No domestic		18 (30)
Japan	No domestic		53 (39)
Republic of Korea	No domestic		19 (39)

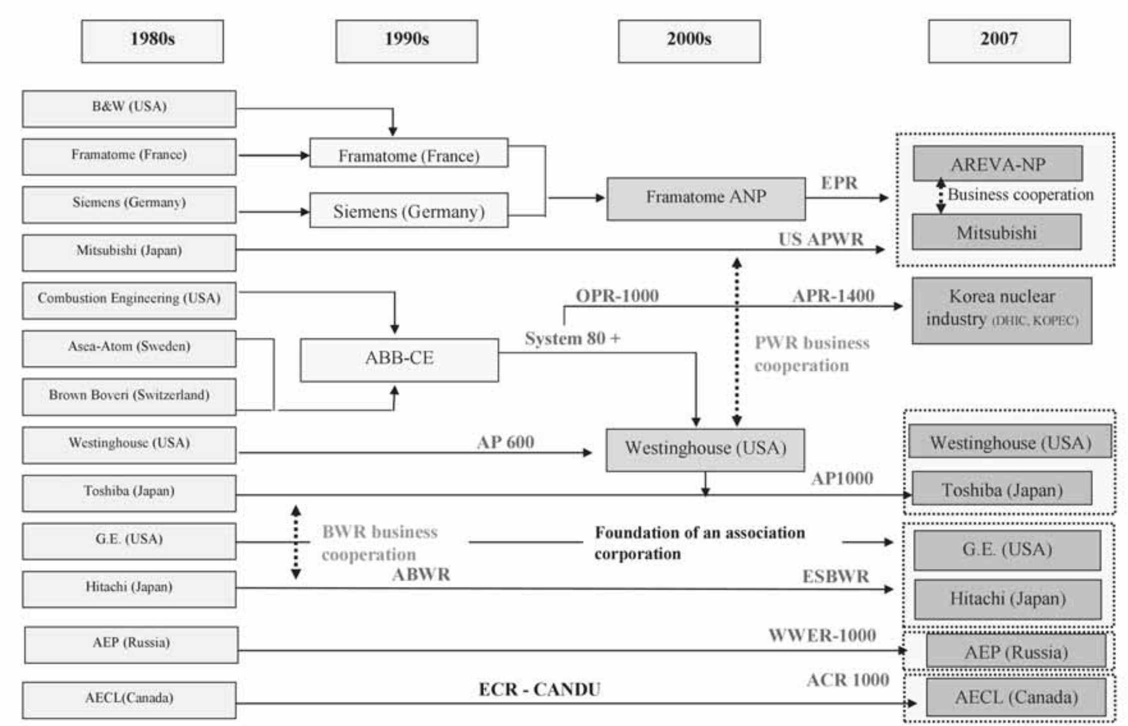
*cost range > US $130/kg U

Source: International Atomic Energy Agency, “Uranium Production and Raw Materials for the Nuclear Fuel Cycle: Supply and Demand, Economics, the Environment, and Energy Security,” in *Proceedings from an International Symposium, Vienna, June 20–24, 2005* (Vienna: International Atomic Energy Agency, 2005), 11.

purchasing nuclear power reactors for the first time may seek such fully integrated contracts, which could enhance or detract from security, depending on one’s perspective.

Most countries that rely on nuclear energy are and will continue to be dependent on others for key elements of their programs. What figure 2 does not show is the extent to which nuclear supply has undergone globalization. Dependence on foreign suppliers is a market reality. For example, in 2007 U.S. owners and operators of nuclear power plants imported 92 percent of the uranium they purchased from twelve

FIGURE 2
Evolution of the Nuclear Reactor Industry



Source: International Atomic Energy Agency, *Nuclear Technology Review 2008* (Vienna: International Atomic Energy Agency, 2008), 9, http://www.iaea.org/About/policy/GC/6C52/6C52InfDocs/English/gc52inf-3s.pdf.

different countries, and they relied on foreign conversion services for about 40 percent of their annual requirements. This is a striking difference from the United States' virtual monopoly on commercial enrichment until the mid-1970s, which evolved from its tight control of military-origin enrichment technology from the 1940s. In 2007, more than six other countries provided 90 percent of total uranium enrichment requirements.[14] Ironically, the only operating U.S. enrichment plant, owned by the U.S. Enrichment Corporation, exports about half its enriched uranium product overseas. With plans for new enrichment plants in the United States, however, more uranium enrichment will be done on U.S. soil, but with foreign technology and ownership.[15] An example from the British nuclear industry shows even greater dependence on foreign sources: the Torness nuclear power plant relies 100 percent on Canadian and Australian uranium ore, Canadian refinement and conversion, and German enrichment. Only fuel fabrication is done in the UK, by Westinghouse.[16]

The security of supply for nuclear energy has become a major focus of nonproliferation policy because of Iran's insistence since 2003 on its "right" to develop a uranium enrichment capability. Citing a failed 1970s investment deal in the French-based Eurodif enrichment entity, Iran has argued that it needs an indigenous capability because it cannot count on a reliable supply of enriched fuel for its future power reactors.[17] Largely in response to the dilemma posed by Iran's noncompliance with its Nuclear Non-Proliferation Treaty obligations, advanced countries have proposed ways to enhance the reliability of supply so that states will have fewer excuses to develop their own enrichment or

14. See the tables in "Uranium Market, 2007," U.S. Energy Information Administration, available at http://www.eia.doe.gov/cneaf/nuclear/umar/table16.html.

15. AREVA and Urenco have plans to build centrifuge enrichment plants in Idaho and New Mexico, respectively, and GE-Hitachi, with investment from Cameco, plans to build a laser enrichment plant in the United States. The exception is the U.S. Enrichment Corporation's plan to build a centrifuge enrichment plant using U.S. gas centrifuge technology.

16. AEA Technology/Environment, "Environmental Product Declaration of Electricity from Torness Nuclear Power Station," Technical Report for British Energy, May 2005.

17. This case involves Iranian investment in the multinational Eurodif uranium enrichment plant. In that case, Shah Reza Pahlavi in 1974 lent $1 billion to help finance construction of Eurodif's enrichment plant and paid $180 million toward the purchase of enriched uranium. After the 1979 revolution, Iranian leaders demanded the return of the money, which was returned in 1991. Unfortunately, by then Iranian leaders changed their minds and demanded fulfillment of the contract, which French officials argued had expired. See Oliver Meier, "Iran and Foreign Enrichment: A Troubled Model," *Arms Control Today*, vol. 36, January/February 2006.

reprocessing. These proposals have included a fuel bank partially funded by the international nongovernmental organization Nuclear Threat Initiative, guaranteed supplies, and shares in enrichment ventures, such as the international uranium enrichment center established at Angarsk by Russia, Kazakhstan, and other states. It is too soon to tell whether these proposals will prove attractive to states seeking nuclear power for the first time.

A more important issue for long-term nuclear supply security is how long the supply of uranium will last under different scenarios of nuclear expansion. At current consumption rates, many agree that the supply of uranium will be sufficient for several decades. Under medium (1–2 percent annual growth) and high (5 percent) expansion scenarios, a shortfall will emerge sooner.[18] The chief executive of Cameco, the Canadian uranium and fuel services corporation, assessed that a gap between demand and supply would begin in 2010 and increase to 2 billion pounds cumulatively by 2020.[19] However, as the price of uranium goes up, so does the profitability of uranium exploration. If more recoverable resources are found, the price would again drop. Should prices rise to $300 a kilogram, it might be profitable to recover uranium from seawater.[20] (For a comparison, the current spot price of uranium is $60 a pound or $132 a kilogram; long-term contracts have lower prices.) Such a price rise would not be devastating for nuclear energy's future, however, because fuel costs make up a small percentage of the cost of generating nuclear electricity.

For those looking beyond the fifty-year horizon, thorium-fueled reactors, plutonium breeder reactors, and fusion reactors all offer, in theory, potential solutions to dwindling uranium resources and greater energy security. Thorium is three times more abundant than uranium,

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18. International Atomic Energy Agency, *Analysis of Uranium Supply to 2050* (Vienna: International Atomic Energy Agency, 2001). Many of the climate change scenarios assume nuclear energy will grow beyond the current rate of 0.7 percent. The 450 Stabilization Scenario introduced in the International Energy Agency's *World Energy Outlook 2007* assumes a 3.5 percent annual growth rate.

19. G. W. Grandey, "The Nuclear Renaissance: Opportunities and Challenges," presentation to IAEA international symposium on "Uranium Production and Raw Materials for the Nuclear Fuel Cycle: Supply and Demand, Economics, the Environment, and Energy Security," Vienna, June 20–24, 2005, 19–24.

20. The International Atomic Energy Agency notes that research by Japan in extracting uranium from seawater has estimated production costs of $750 per kilogram of uranium. International Atomic Energy Agency, *Nuclear Technology Review 2008* (Vienna: International Atomic Energy Agency, 2008), paragraph 30.

but few countries have sought to develop thorium-based reactors because of cost and radiation safety considerations. India, which has a large thorium supply, has been researching and developing this kind of fuel cycle for about fifty years. Breeder reactors produce plutonium, which can then be used for future fuel. No country has successfully commercialized these reactors, although several kinds are under development. Breeder reactor prototypes have all been plagued by safety and operational problems. Fusion reactors are also being researched, and several states are collaborating in the International Thermonuclear Experimental Reactor project. Fusion energy—which joins light elements to release energy, as opposed to fission, which splits atoms to release energy—has been demonstrated for a few seconds. All these paths could provide greater energy security, but all also entail high costs and decades of development.[21]

In sum, for several decades at least, most states will continue to rely on foreign suppliers for key nuclear materials and services—uranium and uranium enrichment, reactors, conversion, fuel fabrication, and, in some cases, spent-fuel reprocessing. Though it is certainly possible for countries to develop nuclear processing capabilities, it makes little economic sense not to use existing suppliers. In addition, there is less risk in such reliance because of the ability to stockpile reactor fuel, in contrast to oil or natural gas supplies. New entrants into the nuclear energy field might be pursuing energy independence, but they will wind up with energy interdependence.

An Affordable and Reliable Electricity Supply

Energy security does not depend solely on an assured supply; it also depends on affordability and reliability. In developing nations, affordable electricity is the key to per capita consumption, which is usually linked to the growth in gross domestic product (GDP).[22] For advanced economies, affordable and reliable electricity is also obviously desirable for continued economic growth. And its importance could

21. The proliferation risks of fusion reactors are highly dependent on the technology chosen. For example, for one assessment of the risks, see www10.antenna.nl/wise/index.html?http://www10.antenna.nl/wise/603/5574.php.

22. According to the Human Development Index, the dividing line between developing and advanced countries is per capita consumption of electricity of 4,000 kWh annually. Eventually, these states should seek to sustain GDP growth and reduce electricity consumption through efficiency.

increase if transportation is transformed to run on electricity. The widespread use of plug-in hybrid vehicles would increase electricity demand, although the order of magnitude is not clear. Initial studies have shown that recharging a hybrid vehicle takes about the same amount of electricity as a dishwasher load.[23] Moreover, hybrid vehicles are likely to be recharged at night, when there is excess generation, transmission, and distribution capacity.

Nuclear reactors are expensive to build but relatively cheap to operate. Thus, nuclear power, along with coal, is used to provide "baseload" electricity—the continuous electricity that is cheapest to produce. The low cost of nuclear fuel makes this possible.[24] Any future carbon "taxes" to reduce greenhouse gas emissions will raise the costs of fossil fuel and therefore increase the cost-competitiveness of nuclear energy. New nuclear power plants, like all other electricity generating plants, will continue to feel the ripple effects of higher oil prices on construction inputs like copper, cement, and steel, but it is unclear how this will affect nuclear power's cost-competitiveness.[25]

Nuclear energy's ability to provide continuous electricity is often cited as a key advantage compared with intermittent sources of electricity like wind and solar power. Yet a reliable electricity supply depends not just on electricity generation but also on transmission and distribution—in other words, on the "grid." Advocates of distributed electricity generation maintain that a reliable supply can best be achieved through many more distributed sources.[26] The current

23. For example, recharging plug-in hybrid electric vehicles requires surprisingly little electricity. The Electric Power Research Institute estimates that recharging these vehicles would draw the same amount of electricity that a dishwasher draws—about 1.4–2 kW of power while charging. In contrast, a big-screen plasma television would draw four times as much electricity as recharging a plug-in hybrid vehicle. See *EPRI Journal,* "Plug-in Hybrids: Building a Business Case," Spring 2008, 8; and Associated Press, "Utilities Say Grid Can Handle Rechargeable Cars," July 23, 2008.

24. On average, the cost of nuclear fuel is 27 percent of the cost of a megawatt-hour, compared with 72 percent for coal plants and 85 to 90 percent for natural gas plants. See Margaret Ryan, *Platt's White Paper: Profitable Operations and Carbon Costs Are Key to Nuclear Power Enthusiasm*, May 2008, 2. Ryan notes that in the case of nuclear fuel, the uranium requires complex processing and stays in the reactor for six years, allowing the cost to be amortized over decades.

25. Stan Kaplan, "Concrete and Steel Requirements for Power Plants," Congressional Research Service memorandum, November 27, 2007.

26. Amory B. Lovins and Imran Sheikh, "Nuclear Illusion," draft subject to further peer review and editing, May 27, 2008, www.rmi.org/images/PDFs/Energy/E08-01_AmbioNucIllusion.pdf.

infrastructure for transmission and distribution (which together cost as much as the power plants themselves) in the United States, as well as in many industrial countries, is designed for these large sources of electricity generation. Distributed sources would require changes to those grids to accommodate them.

A real question for states seeking to introduce nuclear power plants to their electricity grids is the impact of such large, centralized generators of electricity on the reliability of their electricity supply. A general rule of thumb is that no single source of electricity should encompass more than 10 percent of total grid capacity. Because of their transmission grids' capacity limits and the decreased reliability of electricity if one or more of these larger plants were to shut down intermittently, some developing countries now considering nuclear power would be better served by smaller reactors.[27] Yet the reactors currently licensed for sale on the market tend to range from 600 to 1,600 megawatts (MW), and smaller reactors are still largely in the planning stages.[28] The large nuclear reactors that make nuclear energy potentially cost-effective in advanced countries would not provide a realistic means of reliable electricity supply for many of these developing countries. One potential solution is to integrate electricity grids between countries, allowing larger reactors to service larger areas. The efficiency of this approach would vary on a case-by-case basis, depending on the length of transmission lines.

Energy independence is largely a myth. Even Saudi Arabia and Iran import gasoline. Energy security concerns, however, have led a few states in the past to focus on nuclear energy. But until electricity can supplant fossil fuels or produce hydrogen for the transportation sector, nuclear energy will not be fungible with oil, and dependence on foreign sources will continue. Even within the nuclear sector, dependence on foreign sources of uranium, conversion, fuel fabrication, and enrichment services is standard. To enhance energy security, a better

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27. Akira Omoto, director of nuclear power, International Atomic Energy Agency, notes that a sudden disconnection of a large nuclear power plant from the grid creates a serious disturbance to the connected grid, and that the maximum allowable size should be less than 5 to 10 percent of the grid size. Briefing on small and medium-sized reactors, Global Nuclear Energy Partnership, December 11–13, 2007.

28. Westinghouse's IRIS reactor, which could produce from 100 to 335 megawatts electric (MWe), is still in the precertification stage and has been under development for almost a decade. Toshiba's 4S small reactor (10 MWe), which is a small, sodium-cooled fast reactor with a thirty-year life that would not require refueling, could be available after 2015.

plan would be to transform the transportation sector to reduce reliance on fossil fuels and invest in additional capacity and transmission and distribution infrastructure to meet higher demand so that the electricity supply is reliable.[29] Climate change concerns may provide a huge push in this direction.

CLIMATE CHANGE AND NUCLEAR POWER

The concentration of so-called greenhouse gases—carbon dioxide (CO_2), water vapor, ozone, nitrous oxide, chlorofluorocarbons, and methane—in the atmosphere has risen dramatically since preindustrial times. Levels of carbon dioxide alone have risen 40 percent, from about 280 parts per million (ppm) to 380 ppm today. These concentration levels are fed by 26.6 billion tons of carbon dioxide emitted each year. Along a "business as usual" path, annual emissions could grow to 41.9 billion tons by 2030. In fact, carbon emissions have already exceeded estimates in the last few years.

The effects of rising temperatures caused by the concentration of these greenhouse gases are now visible. Computer models estimate that each passing decade could see a 0.2°C rise in temperature, with anticipated dangerous consequences. The best estimates of the Intergovernmental Panel on Climate Change (IPCC) suggest that by 2050, the planet could be between 2.4 and 4°C warmer. Table 2 outlines the IPCC's 2007 estimates of the link between carbon dioxide concentration levels and global temperature increases.

Few now debate whether there is global climate change or what has caused it. Instead, the focus is on how to mitigate and adapt to it. There are two basic questions: What concentration levels are necessary and how quickly do they need to be reached? The answers to these questions have enormous economic implications.[30]

The targets for concentration levels of CO_2 have shifted downward. The Kyoto Protocol, which entered into force in 2005, had as its

29. A. F. Alhajji and Gavin Longmuir, "View: The Perilous Fantasy of Energy Independence," *Daily Times* (Pakistan), February 25, 2007.

30. Juliette Jowit and Patrick Wintour, "Cost of Tackling Global Climate Change Has Doubled, Warns Stern," *The Guardian*, June 26, 2008. Nicholas Stern, author of the October 2006 *Stern Report*, estimated in June 2008 that reducing the carbon concentration below 500 ppm CO_2 would require 2 percent of GDP, in contrast to the 1 percent he had estimated in 2006.

TABLE 2
Carbon Dioxide Concentration Levels and Temperature Rises Above Pre-Industrial Levels

CO_2 concentration level (PPM)	CO_2 equivalent concentration level (PPM)	Global mean temperature > pre-industrial levels	Peaking year for emissions	Global change in emissions in 2050 (as % of 2000 levels)
350–400	445–490	2.0–2.4° C	2000–2015	-50 – -85%
400–440	490–535	2.4–2.8° C	2000–2020	-30 – -60%
440–485	535–590	2.8–3.2° C	2010–2030	+5 – -30%
485–570	590–710	3.2–4.0° C	2020–2060	+10 – +60%

Source: Intergovernmental Panel on Climate Change, 2007.
PPM = Parts Per Million

goal a concentration level of 550 ppm CO_2 equivalents. Now, there is a growing consensus that lower levels—450 ppm—are needed to avoid the worst effects of climate change. Stabilization of CO_2 concentration levels at 400 to 440 ppm, according to the IPCC, could limit the eventual rise in global average temperature to around 2.4 to 2.8°C. Most agree that the challenge is to reduce annual emissions to a level where the concentration of greenhouse gases stabilizes at slightly higher levels than today.

Estimates of when emissions must begin to decline shape the urgency of the problem. The December 2007 Bali "road map" for greenhouse gas reductions suggested that emissions could be allowed to peak in the next ten to fifteen years, but then must be reduced to very low levels—well below half of 2000 emissions levels by 2050. The Bali Action Plan stated that "delay in reducing emissions significantly constrains opportunities to achieve lower stabilization levels and increases the risk of more severe climate change impacts."[31] According to the IPCC, limiting the average increase in global temperatures to a maximum of 2.4°C above preindustrial levels would require that all CO_2 emissions peak by 2015 and fall between 50 and 85 percent below 2000 levels by 2050. The *Human Development Report 2007/2008* underscored this, assessing that delaying reduction of emissions until 2020 would require even greater reductions later (8.2 percent annually until 2050). A "sustainable emissions path" would require an earlier peak (between

31. United Nations Framework Convention on Climate Change, "Bali Action Plan," Decision 1/CP.13 FCCC/CP/2007/6/Add.1, http://unfccc.int/files/meetings/cop_13/application/pdf/cp_bali_action.pdf.

2012 and 2015), followed by rapid declines (30 percent by 2020, and then another 80 percent by 2050).[32]

The approaches to lowering emissions are well known: improving energy efficiency, decarbonizing the supply of electricity and fuels (through shifting fuels, capturing and storing carbon, and building more zero-carbon fuel sources like nuclear and renewable energies), and biological storage in forests and agricultural soils.[33] Energy efficiency tops the list of necessary high-impact mitigation measures. According to the IEA, measures to improve energy efficiency are "the cheapest and fastest way to curb demand and emissions growth in the near term," but getting below 2000 emissions levels would require immediate policy action and unprecedented technological transformation.[34] Most of the IEA's scenarios for slowing the growth of carbon emissions rely heavily on efficiency improvements.[35] In the popular 2004 "wedge" analysis by Princeton University scientists Stephen Pacala and Robert Socolow, four of the fifteen wedges described focused on efficiency.[36]

Given the enormity of the challenge, it is clear that no single technology or approach can "fix" climate change. Much as a sensible food diet would prohibit binging or purging, a sensible carbon diet needs to balance energy inputs. In this respect, nuclear energy will neither be "the" solution, nor is it likely to be purged in favor of other technologies. Japan, France, China, Russia, India, and the United States—the states with more than two-thirds of current global nuclear reactor capacity—are unlikely to phase out nuclear energy anytime soon. It is nonetheless reasonable to pose these questions: (1) How much more nuclear energy would be needed to have a significant impact? (2) Could that much nuclear energy be brought online in anywhere near the time required from a climate perspective? (3) Are the opportunity costs of such an expansion acceptable?

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32. United Nations Development Program, *Human Development Report 2007/2008: Fighting Climate Change—Human Solidarity in a Divided World* (New York: United Nations Development Program, 2007), 119.

33. Stephen Pacala and Robert Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, August 13, 2004, 968–972.

34. International Energy Agency, *World Energy Outlook 2007*, 42.

35. See, for example, the International Energy Agency's "Alternative Scenario," *World Energy Outlook 2006*. Assuming governments adopt a variety of policies now under consideration to reduce emissions, the policies that encourage the more efficient production and use of energy contribute almost 80 percent of avoided CO_2 emissions.

36. Ibid.

NUCLEAR ENERGY'S CONTRIBUTION TO MITIGATING GLOBAL CLIMATE CHANGE

Electricity production generates 41 percent of the world's energy-related carbon emissions. Compared to coal and natural gas in a climate change context, nuclear energy has obvious advantages. Like renewable energy sources such as wind, solar, biofuels, and hydropower, nuclear energy emits no carbon dioxide as it generates electricity.[37] Like coal, existing nuclear power plants produce large amounts of base-load electricity but at higher costs per kilowatt-hour (kWh) (coal is 4–5 cents per kWh; nuclear is 7 cents per kWh).[38] This ability to generate electricity continuously is often cited as an advantage of nuclear energy over wind and solar energy.

Estimates of nuclear energy's current contribution to mitigating climate change can be misleading. When AREVA, the French nuclear conglomerate, suggests that nuclear energy is currently contributing to lowering global CO_2 emissions by 10 percent, it is likely calculating that coal plants, if they were to replace all existing nuclear power plants, would emit about 2.2 billion tons of CO_2 per year.[39] Another calculation is that

37. Nuclear power plants emit no carbon dioxide in their operations, but the entire life cycle of producing electricity from nuclear power does emit carbon dioxide. These are roughly comparable to the emissions of other zero-carbon sources such as wind, hydro and photovoltaics. See, for example, AEA Technology/Environment, "Environmental Product Declaration of Electricity from Torness Nuclear Power Station," Technical Report for British Energy, May 2005, which estimates CO_2 emissions to be 5 grams per kWh, compared with coal at 900 grams per kWh. Note, however, that the Torness analysis excluded emissions from the construction of the supporting facilities, save for the power plant, spent-fuel storage, and high-level waste storage facility. It also excluded emissions from dismantling facilities, save for the power plant. See also the Vattenfall Environmental Production Declaration (www.environdec.com/reg/climate/epdc21e.pdf), which gives a CO_2 equivalent emission of 3.67 grams per kWh. Higher figures are found in Jan Willem Storm van Leeuwen and Philip Smith, "Nuclear Energy: the Energy Balance," July 30, 2005, available at http://www.stormsmith.nl/report20050803/chap_2.pdf.

38. Massachusetts Institute of Technology, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge: Massachusetts Institute of Technology, 2003), available at http://web.mit.edu/nuclearpower. These figures obviously vary over time and from country to country and could change if policies are adopted to limit carbon dioxide emissions. However, the low capital costs of coal plants and coal generally make it a cheaper source of electricity than nuclear power.

39. See AREVA's 2006 disclosure to the Carbon Disclosure Project's fourth Greenhouse Gas Emissions Questionnaire, available at www.cdproject.net. AREVA estimated that a 1 GWe coal plant currently emits 6 million tons of CO_2 per year. If coal were to replace global nuclear

a 1 gigawatt electric (GWe) (a large, billion-watt) plant operating at 90 percent of capacity would save the emission of 1.5 million metric tons of carbon annually if it were built in place of a modern coal electric plant.[40] Accordingly, current nuclear power plants "save" 556 million tons (or 0.5 gigatons, Gt) of CO_2 annually. If nuclear energy were substituted for a mix of energy sources (coal, oil, and gas), it would save a little less CO_2 per year, on the order of 0.4 Gt of carbon.

Many of the estimates of nuclear energy's future carbon savings assume that nuclear power plants would be built in place of new coal electric plants. It is unlikely that nuclear power plants will displace just new coal plants, however. Nuclear energy that displaces natural gas, wind, solar, or renewables would have less impact on reducing carbon emissions. Ultimately, decisions about investing in large versus small generation facilities and centralized versus distributed generation will affect the extent to which nuclear energy might displace other zero-carbon options.[41] This is important because smaller, distributed electricity generation may be a more favorable option for developing countries, where 70 percent of the projected growth in electricity demand is expected by 2050.

Two key countries to consider are China and India. China is adding about 1,000 MW of coal-fired capacity per week; India is adding that amount every two weeks.[42] Estimates suggest that 86 percent of the world's incremental coal demand through 2030 will come from China and India.[43] China plans to add 50 GWe nuclear capacity by 2020, and India hopes to add close to 40 GWe in the same time period. Given the anticipated rates of economic growth in China and India, it is unlikely, however, that new nuclear power plants will replace plans to build coal plants. Instead, they are likely to be built in addition to coal.

capacity (about 371 GWe), the resultant carbon emissions would be about 2.2 billion tons per year. This is a bit misleading because coal plants operate at lower capacity factors—about 60 percent lower than nuclear power plants. Emissions can vary considerably according to the type of coal burned and the technology of the plants.

40. The International Panel on Fissile Materials estimates that when compared with an equivalent modern coal plant, 1 GWe of nuclear capacity operating at an average capacity factor of 90 percent reduces the amount of carbon released to the atmosphere by about 1.5 million metric tons annually. See International Panel on Fissile Materials, *Global Fissile Material Report 2007* (Geneva: International Panel on Fissile Materials), 87.

41. See the arguments made by Lovins and Sheikh, "Nuclear Illusion."

42. Adding 1,000 MWe has sometimes meant adding two coal plants per week, because the plants often produce 500 MWe of capacity.

43. See www.pewclimate.org/global-warming-basics/coalfacts.cfm.

Current trends in nuclear power provide important context. The IEA estimates that without significant policy changes, nuclear energy could grow annually by 0.7 percent, for a total 15 percent increase by 2030. This would equal about 415 GWe, up from the current 371 GWe, or an annual build rate of three reactors per year.[44] At this rate, nuclear energy would actually decline from a 16 percent market share to 10 percent as electricity demand increases. CO_2 concentrations would go up, despite this nuclear energy capacity's ability to offset between 11 and 13 Gt of carbon through 2030. In this business-as-usual projection, no big policy changes would be implemented, carbon emissions would rise, and nuclear energy's share of electricity generation would decline.

With significant policy changes, nuclear energy might be able to contribute more to global climate change mitigation. There is a wide range of climate change scenarios that outline different paths to achieving reductions, including nuclear power. There are also many scenarios that take nuclear energy growth as their starting point and assess the climate change contributions. A representative mix is provided in table 3, which outlines the different implications for nuclear energy in four climate change scenarios produced by the IEA, the 2004 Pacala-Socolow "wedge" analysis, and a 2003 Massachusetts Institute of Technology (MIT) analysis of two levels of significant nuclear growth (1,000 and 1,500 GWe).

Such climate change scenarios illuminate the trade-offs between approaches and energy sources and across power, transportation, industrial, and other sectors. Table 4 summarizes some of the differences among the four IEA scenarios.

The first scenario—the Alternative Policy Scenario—projects how policies in 2006 on climate change and energy would affect the global energy mix and carbon reductions. Nuclear energy capacity would grow

44. This assumes 27 GWe of reactors are retired in Europe. The U.S. Energy Information Administration (EIA) estimates 482 GWe for 2030, or an annual increase of 1.3 percent, but assumes planned phase-outs of nuclear power in some countries in Europe would be delayed. EIA projections take into account GDP growth, energy demand, end-use sector, and electricity supply, estimating the contribution that nuclear energy will make as a percentage of the total electricity supply. This percentage is estimated to stay even or rise slightly. Some of the limitations of EIA projections are that the nuclear energy projections are done "off-line"—that is, the sophisticated computer model for estimating other sources of energy is not used for the nuclear case. In addition, the estimates are aggregated into regions, with just a few country-specific breakouts. Further, retirements and the behavior of Western Europe are considered highly uncertain ("wildcards"), and so estimates on those tend to be more conservative.

TABLE 3

Comparison of IEA Climate Change Scenarios, the Pacala-Socolow Wedge Analysis and 2003 MIT Growth Scenarios

Scenario	Goal	Target Year	Assumptions	CO_2 Level; Annual Target	Nuclear Capacity by Target Year	Nuclear Share of CO_2 Reductions
Alternative Policy* Scenario	None	2030	Current policies implemented no carbon capture & storage (CCS). Nuclear phase-outs delayed	550 ppm; 34 GtC	Add 154 GWe for total of 525GWe	10%
450 Stabilization Scenario	450 ppm by 2030	2030	Rely on CCS, 2nd generation biofuels	450 ppm; 23 GtC	Add 462 GWe for total of 833 GWe	16%
Accelerated Technology (ACT) Scenario	Stabilize current emissions by 2050	2050	$50/t carbon price by 2030 Minimum cost path	485 ppm; 27 GtC (2050); 14 GtC (2100)	Add 960 GWe for total of 589 GWe (assuming all existing plants retired by 2050)	6%
Blue Scenario	Halve emissions by 2050	2050	$50/t carbon price by 2020, rising to $200/t C in 2030 Minimum cost path	445 ppm; 14 GtC	Add 1280 GWe for total of 909 GWe (assuming all existing plants retired by 2050)	6%
Pacala-Socolow "Wedge" Analysis	Stabilize current emissions by 2050	2050	Described options for achieving "wedges" that would reduce carbon emissions by 1 Gt/year by 2050	500 ppm; 27 GtC	For net gain of 700 GWe (assuming all existing plants retired by 2050), add 1071 GWe	14.5%**
2003 MIT	Evaluate actions to maintain nuclear power as a significant option	2050	$200/t C price needed to make nuclear cheaper than other options	No target levels	For targets of 1000 and 1500 GWe (assuming all existing plants retired by 2050), add 1371 or 1871 GWe capacity	15-25%

Sources: The Alternative Policy Scenario appeared in the IEA's *World Energy Outlook 2006*; the 450 Stabilization Scenario appeared in the IEA's *World Energy Outlook 2007*; the Alternative Technology Scenario was first published in the IEA's *Energy Technology Perspectives 2006* and updated in the *Energy Technology Perspectives 2008*; and the Blue Scenario appears in the *Energy Technology Perspectives 2008*.

*The Alternative Policy Scenario is so called because it does not assume a "business-as-usual" approach in making projections for different energy sources. Instead, it assumes that countries will implement the plans they announced regarding climate change in 2006.

**If we assume that nuclear would replace a mix of fuels, rather than just coal, the percent reduction drops to 6%.

TABLE 4
Differences Among the International Energy Agency's Four Climate Change Mitigation Scenarios

Alternative Policy Scenario	
Assumes that emission reduction measures now under consideration by governments will be implemented, shaving years off of the widespread deployment of technologies in wind, hydropower, renewables, hybrid cars, and building efficiency (but not carbon capture and storage)	
Stabilization	550 parts per million (ppm) of carbon dioxide (CO_2)[a]
Temperature increase	3°C above preindustrial levels
Most carbon savings?	Efficiency (4/5?)
Nuclear capacity growth	1.6 percent annual average growth; 7 plants per year
Where?	Add 16 GWe in the United States, 24 GWe in China, and 36 GWe in countries belonging to the Organisation for Economic Cooperation and Development (OECD) (assuming nuclear phaseouts are delayed)
450 Stabilization Scenario	
Would require annual energy-related CO_2 emissions to peak in 2012 at 30 gigatons (Gt) of carbon per year (they are now 27 Gt carbon per year) and then fall to 23 Gt in 2030	
Stabilization	450 ppm
Temperature increase	2.4°C above preindustrial levels
Most carbon savings?	Improved efficiency in fossil-fuel use in industry and buildings (25 percent); carbon capture and storage for carbon-based fuels (21 percent); renewables in the power sector (19 percent); nuclear (16 percent); lower electricity demand (13 percent); second-generation biofuels in the transportation sector (4 percent)
Nuclear capacity growth	3.5 percent annual average growth; 22 plants per year
Where?	Not applicable
ACT (Accelerated Technology) Scenario	
Would stabilize global carbon emissions by 2050; assumes that by 2030, countries would price carbon reductions at $50 a ton	
Stabilization	485 ppm by 2050; 520 ppm by 2100
Temperature increase	2.8–3.2°C above preindustrial levels
Most carbon savings?	End-use fuel efficiency (28 percent); renewables (16 percent); end-use electricity efficiency (16 percent); end-use fuel switching (1 percent); carbon capture and storage (CCS) power generation (10 percent); CCS industry and transformation (6 percent); power generation efficiency and fuel switching (17 percent); nuclear power (6 percent)
Nuclear capacity growth	3.5 percent annual average growth; 24 plants per year
Where?	OECD North America (29 percent), OECD Europe (20 percent), OECD Pacific (15 percent), China and India (21 percent), other (15 percent)
Blue Scenario	
Seeks to halve global carbon emissions by 2050, peaking the annual emissions in 2018 and then dropping below current levels; assumes countries would price carbon reductions at $50 a ton by 2020, rising to $200 a ton 10 years later	
Stabilization	445 ppm by 2050
Temperature increase	2.8–3.2°C above preindustrial levels
Most carbon savings?	End-use fuel efficiency (24 percent); renewables (21 percent); end-use electricity efficiency (12 percent); end-use fuel switching (11 percent); CCS power generation (10 percent); CCS industry and transformation (9 percent); power generation efficiency and fuel switching (7 percent); nuclear (6 percent).
Nuclear capacity growth	32 plants per year; specifically, 16 reactors per year from 2005 to 2015, 18 a year from 2015 to 2025, 24 per year from 2025 to 2035, and 46 per year from 2035 to 2050
Where?	OECD North America (26 percent), OECD Europe (18 percent), OECD Pacific (14 percent), China and India (26 percent), other (16 percent)

Sources: The Alternative Policy Scenario appeared in the IEA's *World Energy Outlook 2006*; the 450 Stabilization Scenario appeared in the IEA's *World Energy Outlook 2007*; the Accelerated Technology Scenario was first published in the IEA's *Energy Technology Perspectives 2006* and updated in *Energy Technology Perspectives 2008*; and the Blue Scenario appears in the IEA's *Energy Technology Perspectives 2008*.

[a]The Alternative Policy Scenario is consistent with 550 ppm stabilization, but this is an outcome of policy choices, rather than a policy goal, unlike the ACT and Blue scenarios, which had particular policy objectives.

1.6 percent annually, which is double the rate of most economic projections; and it would decline in its share of electricity production but would contribute 10 percent of carbon reductions. This is primarily because this scenario assumes that no carbon capture and storage will be in place to make coal electric power cleaner. The cumulative growth in nuclear energy to 2030 would be about 30 percent.

The second scenario—the 450 Stabilization Scenario—would require more than doubling nuclear energy capacity (833 GWe) by 2030. Nuclear capacity would need to grow 3.5 percent annually, or by twenty-two reactors per year, and would contribute 16 percent of the carbon offsets. The IEA has stated that exceptionally vigorous and immediate policy action would be needed and that nuclear energy and carbon capture and storage would face major policy and regulatory hurdles that would take some time to resolve.[45]

The third scenario—the Accelerated Technology (ACT) Scenario—seeks to stabilize emissions at current levels. Nuclear energy would contribute 6 percent of carbon reductions if twenty-four large reactors (1 GWe each) could be built each year.

The fourth scenario—the Blue Scenario—seeks to halve emissions from current levels by 2050. Again, nuclear energy's contribution to carbon reductions would be 6 percent, the lowest of all alternatives, and an average of thirty-two reactors would have to be built annually. Both the ACT and Blue Scenarios reflect historical limits on reactor construction and assume that a maximum of thirty reactors could be built per year.[46] Nuclear expansion is thus limited to building 1,270 GWe by 2050. The IEA assessed that building 2,000 GWe could be cost-effective but probably not feasible or acceptable, because this would imply a massive-scale reprocessing of spent fuel. The Blue Scenario also assumed that current generation reactors (Generation III and III+) would be built through 2030 and that the next generation of reactors (Generation IV) could be widely deployable by 2050. Capacity in 2050 would reach 900 GWe, given retirements. This is about two and one-half times greater than current levels.

The Pacala-Socolow wedge analysis, published in *Science* in 2004, demonstrated how current technologies, including nuclear energy, could

45. International Energy Agency, *World Energy Outlook 2007*, 208.

46. The actual deployment of reactors in the Blue Scenario would be sixteen reactors per year in the first decade (to 2015), eighteen reactors a year in the second decade, twenty-four reactors a year in the third decade, and forty-six reactors a year from 2035 to 2050.

help reduce carbon emissions.[47] Working back from a desired reduction of 7 billion tons of carbon per year by 2050, Pacala and Socolow described a menu of fifteen options for reducing annual emissions by 1 billion tons each by 2050. It would be necessary to fill seven wedges; one nuclear wedge would require adding 700 GWe capacity to current capabilities if it were to replace modern coal-electric plants.[48] Nuclear power would contribute one-seventh (or 14.5 percent) of the needed carbon reductions.[49] This wedge analysis concluded that the rate of growth in nuclear power—building about fifteen plants a year—was reasonable, given historical rates of building in the 1980s. However, virtually all the operating reactors will have to be retired by 2050, even if their operating lives are extended to sixty years. Therefore, twenty-five new reactors would need to be built each year through 2050 to account for retirements (which would total 1,070).

The MIT scenarios, contained in the 2003 study *The Future of Nuclear Power*, were motivated by a concern that nuclear power would not be a viable option to help mitigate climate change unless major expansion occurred. This study assessed the feasibility of achieving 1,000 and 1,500 GWe levels of expansion by 2050. These levels of expansion would require building, respectively, thirty-two and forty-five reactors a year. Note that the build rate assumes an average 1,000 megawatts electric (MWe) (or 1 GWe) capacity. However, several of the current designs range from 1,150 to 1,600 MWe, requiring fewer reactors to be built.

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47. Pacala and Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, August 13, 2004.

48. Critics maintain that Pacala and Socolow underestimated the number of wedges that would be required because of assumptions about efficiency, among other things. See, for example, an interview with the New York University emeritus professor Martin Hoffert at http://thebreakthrough.org/blog//2008/04/post_1-print.html.

49. A Natural Resources Defense Council (NRDC) analysis has shown that adding 700 GWe capacity by 2050, at an average rate of 14 GWe per year, would result in 0.2^{O} C savings in global temperature rise. Nuclear energy's contribution to carbon reductions in the NRDC analysis is lower than in the wedge analysis (6 percent rather than 14.5 percent) because NRDC assumes, among other things, that nuclear energy offsets a mix of other electricity sources (not just coal); thus, 1 GWe per year reduces carbon by 1.2 million tons annually. Given the implausibility of making direct trade-offs between nuclear and coal, this approach is likely to be more realistic. The analysis also assumes an 85 percent operating capacity, rather than 90 percent. See Thomas B. Cochran, "The Contribution of Nuclear Power to Climate Change Mitigation," presentation to the Department of Nuclear Engineering Colloquium, University of California, Berkeley, March 10, 2007.

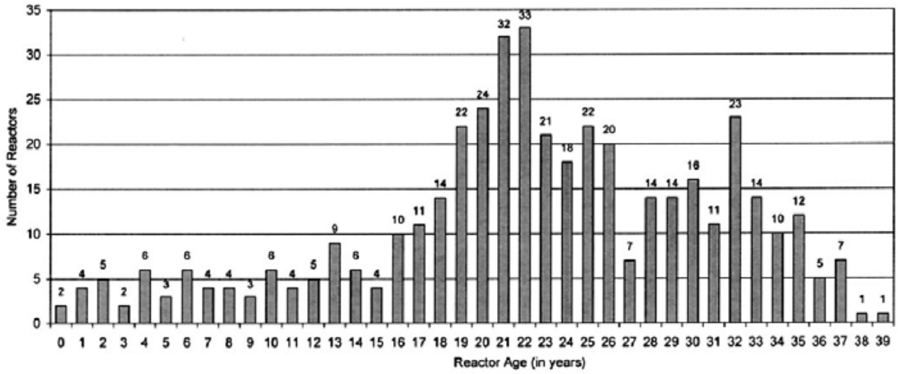
TABLE 5
Comparison of Capabilities Under Different Nuclear Growth Scenarios for 2030 and 2050

	2030			2050			
	IEA Ref	APS	450 ppm	ACT	Blue	Wedge	MIT 2003
Capacity (GWe)	415 GWe	525 GWe	833 GWe	589 GWe	909 GWe	1071 GWe	1500 GWe
Total CO_2 emissions (gigatons Gt), heat avoided (°C)	9.6 Gt .05°C	11.17 Gt .05°C	22.6 Gt .06°C	35.2 Gt .09°C	46.9 Gt .12°C	52.9 Gt .14°C	68.6 Gt .18°C
New build reactors *(annual build)*	71 *(3.5)*	154 *(7.5)*	462 *(23)*	218 *(5.5)*	538 *(13.5)*	700 *(17.5)*	1129 *(28)*
New build cumulative carbon (Gt)& heat reductions (°C)	.8 Gt —	2 Gt .01°C	8.7 Gt .02°C	8 Gt .02°C	19.7 Gt .05°C	25.7 Gt .07°C	41.4 Gt .11°C
New build share of needed reduction (percent)	.8%	2.1%	9.4%	4.5%	11.2%	14.6%	23.4%
Actual share of reduction (percent), assuming retirements	.8% (27 retired by 2030)			— —	3.4% (6.1 Gt)	6.9% (12.1 Gt)	15.5% (27.8 Gt)
Build rate required to reach goals assuming retirements by 2050*	—	—	—	*24*	*32*	*26.75*	*46.75*

Assumptions about retirements: 0 through 2030; 371 through 2050. For 2030 scenarios, assumed needed reduction would be 92 GT carbon; for 2050, 175 GT.
*These numbers assume each plant is 1000 MWe. However, the latest proposed reactors range from 1,150 to 1,600 MWe. The actual number of plants would vary according to their capacity.

The more aggressive climate change mitigation scenarios would require high rates of nuclear power plant construction in the next twenty years. For the most part, this new construction can be considered additional capacity, because states may choose to extend the forty-year lives of their existing plants. Many of the nuclear growth scenarios assume that existing reactors will continue operating through 2030. Through 2050, however, virtually all reactors will need to be replaced, and therefore the contribution of new nuclear power plant construction to reducing carbon emissions is lowered by about 0.5 Gt of carbon a year—

FIGURE 3
Age of Currently Operating Reactors as of December 2006



Source: Power Reactor Information System, International Atomic Energy Agency, 2008.

the amount that existing capacity “saves.” Figure 3 shows the ages of the nuclear reactors that are currently operating.

Given that reactors are likely to require at least a decade from licensing to connection to the grid, the first decade is likely to see the completion of projects currently under way. The World Nuclear Association estimates that fifty-six reactor projects could be completed by 2014, for a net 54 GWe in added capacity. This is an average of eight reactors per year. This slower rate of deployment means that more reactors would have to be built later to achieve carbon reduction levels. For example, the 450 Stabilization Scenario envisions 462 GWe in additional capacity. If only 56 GWe is added by 2014, 406 GWe must be built between 2015 and 2030, or an average 25 GWe each year. Similar calculations (assuming eighty reactors built in the first ten years of a forty-year time frame) for the other scenarios yield higher average build rates for later years: for ACT, about twenty-nine a year; for the Blue Scenario, forty a year; for the wedge analysis, thirty-three a year; and for the MIT 1,500 GWe analysis, almost sixty a year.

At the height of past nuclear power expansion, 33 reactors were connected to the electricity grid in both 1984 and 1985. These reactors were begun a decade before that. Over a fifty-year period in all, the average annual number of plants connected to the grid was 11 per year. From 1976 to 1985, 217 plants were connected to the grid, or an average of 22 per year. Industry advocates note that after the Three Mile Island accident in 1979, many planned reactors were canceled, and therefore the rate of construction during that time could have been twice as large.[50] If the nuclear infrastructure to support such construction were available today, some of the scenarios depicted might be possible to implement. However, in the last fifteen years, there have been six or fewer construction starts per year worldwide, and production and construction capacity has shrunk accordingly.

If major reductions in carbon emissions need to be made by 2015 or 2020, a large-scale expansion of nuclear energy is not a viable option. In the United States, no new nuclear reactors can be expected to operate before 2015.[51] Worldwide, few reactors that are not already in the licensing process or under construction could be operational before 2020. This rate of building means that a higher number of reactors would need to be built between 2020 and 2050, as suggested above. Current construction will dominate the first decade—about eight reactors a year—and only dramatic policy changes would help accelerate production capabilities. These changes are likely to focus on helping reduce the cost of new nuclear power, but they are unlikely to make a big impact on mitigating safety, waste, and proliferation concerns—the other three traditional challenges of nuclear energy. In sum, the more urgent climate change requirements are, the less likely nuclear energy will be able to meet these challenges. The following section explains why.

PARTICULAR CHALLENGES OF NUCLEAR ENERGY

There are no secrets about the challenges of nuclear energy, just vociferous debates about whether and how they can be surmounted.[52] Costs are hotly debated, particularly in an industry where relatively few power plants have been built in the last twenty years. Safety is a perennial concern. Waste issues are generally put off indefinitely.

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50. According to testimony by David Lochbaum of the Union of Concerned Scientists, in the United States, 253 nuclear power plants were ordered (from 1953 to 2008); 71 were canceled before construction, and 50 were canceled after construction started. The United States currently has 104 operating power reactors. See http://www.ucsusa.org/assets/documents/nuclear_power/20080312-ucs-house-nuclear-climate-testimony.pdf.

51. Ed Cummins, Westinghouse, remarks to forum on "Potential Pathways and a New Environment for Nuclear Energy," Center for Strategic and International Studies, Washington, June 26, 2008.

52. See, for example, Massachusetts Institute of Technology, *Future of Nuclear Power*, 42; Charles Ferguson, *Nuclear Energy: Balancing Benefits and Risks* (New York: Council on Foreign Relations, 2007); and Keystone Center, *Nuclear Power Joint Fact-Finding* (Keystone, Colo.: Keystone Center, 2007).

Proliferation concerns have been a topic of quiet debate, focused often on the "sensitive" parts of the fuel cycle—uranium enrichment and spent-fuel reprocessing—rather than on power reactors. Even if states agree that there is an urgent need to reduce carbon emissions, these challenges will present hurdles wherever nuclear power plants are built, but particularly in developing countries.

Real and Relative Costs, and the Importance of Carbon Pricing

Nuclear power plants are expensive to build but relatively inexpensive to operate, particularly because their fuel costs are low compared with alternatives. For example, the price of natural gas accounts for 85 percent of the variable cost of a kilowatt-hour, whereas nuclear fuel accounts for 27 percent. This means that as the cost of fossil fuels rises, either due to short supply or because CO_2 emissions may be regulated in the future, nuclear power will become relatively more competitive. There is already evidence in the United States that coal plants may become increasingly difficult to build because of public awareness of their environmental impact. U.S. nuclear industry executives have suggested that a carbon-pricing framework would be necessary to provide incentives for utilities to build more than a handful of nuclear power plants.

A big uncertainty are the costs of constructing new nuclear power plants. Key factors affecting these costs include the creditworthiness of the companies involved in building the reactors, the cost of capital (especially debt) over the next decade, and the risk of cost escalation due to construction delays and overruns. In particular, good project management is critical to keeping costs down.

Unfortunately, there are very few data on new construction, and using historical costs as a baseline can be problematic. In the United States, cost overruns have been the norm, not the exception.[53] The real costs of new nuclear power plants may not be known for years. In

53. In a May 2008 report on nuclear power, the Congressional Budget Office compared U.S. utilities' projections of average overnight costs with actual overnight costs (this excludes financing costs) of seventy-five reactors built from 1966 to 1977 and found an average overrun of 207 percent. For the forty plants constructed after Three Mile Island in 1979, cost overruns exceeded 250 percent. Congressional Budget Office, "Nuclear Power's Role in Generating Electricity," May 2008, 16–17. There is more available data on cost overruns in the United States, but a recent foreign example is AREVA's EPR reactor being built in Olkiluoto, Finland, which is one and a half years behind schedule and costing over $1 billion more than estimated.

fact, Moody's stated in a special October 2007 report that "the ultimate costs associated with building new nuclear generation do not exist today—and that the current cost estimates represent best estimates, which are subject to change."

In the United States, Moody's estimated in October 2007 that the all-in costs of a new nuclear power plant could range from $5,000 and $6,000 per kW, which translates into $5 billion to $6 billion for a 1,000 MWe plant.[54] Such an estimate includes all the costs incurred during construction, including financing costs, which can add anywhere from 25 to 80 percent to the cost estimate. Vendor estimates since then have varied between a low of $2,865 per kW for the South Texas Project Units 3 and 4 (this was their low estimate in March 2008, versus a midrange estimate of $3,200 per kW) to $5,746 per kW for Calvert Cliffs 3 in Maryland. These costs are overnight costs—that is, they do not include the financing costs.[55]

Figure 4 shows how the costs break down for different kinds of electricity generation sources. Note that the figures for nuclear energy in the graph are significantly lower than current estimates now show. However, the figure illustrates how much greater capital costs factor into the total cost for nuclear energy than for alternatives.

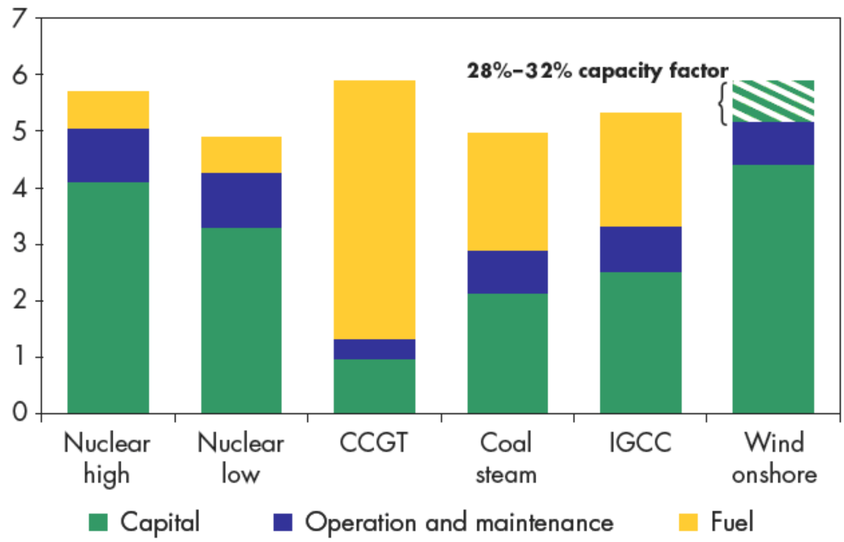
One of the reasons why capital costs are higher for nuclear power plants is that they take longer to build than the alternatives. For example, wind plants require eighteen months to build, combined-cycle gas turbines need thirty-six months, and nuclear power plants take at least sixty months. Up-front costs are incurred throughout the ten years before the plants start to generate revenue. Therefore, it is unsurprising that financing costs can account for between 25 and 80 percent of the total cost of construction.

The cost of capital can vary significantly among countries. In the United States, it may even vary from market to market, depending on whether the utility building a nuclear power plant is operating in a regulated or deregulated market. In deregulated markets especially, investors may require higher equity-to-debt ratios, making it more costly

54. Moody's estimated existing nuclear plants at $2,700 to $3,500 per kW; $1,700 to $2,200 per kW for existing coal plants; and $700 to $900 per kW for combined-cycle natural gas plants. The second most expensive option is integrated gasification combined-cycle coal plants, at between $3,300 and $3,700 per kW. Moody's Corporate Finance, Special Comment, "New Nuclear Generation in the United States," October 2007.

55. Stan Kaplan, "Power Plants: Characteristics and Costs," CRS Report for Congress RL34746, Congressional Research Service, November 13, 2008.

FIGURE 4
Comparative Costs for Generating Electricity (U.S. cents per kilowatt-hour)



Source: International Energy Agency, *World Energy Outlook 2006* (Paris: International Energy Agency), figure 13.7.

Note: CCGT = combined-cycle gas turbines; IGCC = integrated-gasification combined cycle. The "nuclear high" case assumes a high construction cost of $2,500 per kilowatt, while the low case assumes a cost of $2,000 per kilowatt. Parameters for the low discount rate are found in table 13.10 of *World Energy Outlook 2006*, but the real after-tax-weighted average cost of capital is 6.7 percent. The high-discount scenario has a 9.6 percent rate, and in that scenario, nuclear costs are higher than all others.

for merchant utilities.[56] In a regulated market, where utilities can count on an authorized rate of return, lenders may be more comfortable with a higher ratio of debt in the financing. A telling anecdote about how the private capital market feels about new nuclear power plants is the suggestion by financial market analysts in early 2008 that U.S. utilities seeking to build new nuclear power plants could see their excellent credit ratings drop to a single "B" rating.[57] By late 2008, some financial analysts were suggesting that the utilities could do little to salvage their credit ratings.[58] In mid-September, Constellation Energy's credit rating

56. U.S. Department of Energy, "Moving Forward with Nuclear Power: Issues and Key Factors," Final Report of the Secretary of Energy Advisory Board, Nuclear Energy Task Force, January 10, 2005, 1-2, 3-2.

57. Comments by Jim Hempstead, Moody's, at Platt's Fourth Annual Nuclear Energy Conference, Bethesda, Md., February 5–6, 2008.

58. Stephen Maloney, Towers Perrin Inc., presentation to Platt's Nuclear Conference, September 15, 2008.

was downgraded in a domino effect of Lehman Brothers' bankruptcy filing.

A global tightening of risk management standards in the wake of the current economic crisis could imperil the nuclear industry in particular, because a reactor entails such a large investment (between $5 billion and $10 billion per plant) relative to the typical financial resources of electric utilities. In this environment, potential government financing (loan guarantees, tax credits, and the like) can make a big difference. In the United States, there has been a major push to subsidize new nuclear power plants through federal loan guarantees, delay insurance, and other subsidies for the first six new nuclear reactors as well as funding from the U.S. Department of Energy (DOE) for what are called "first of a kind" reactors. Given the lack of recent experience in building nuclear power plants, delay insurance (which would underwrite the risk of substantial delays in construction) and funding for "first of a kind" reactors will be particularly important. One analyst estimates that the 2007 loan guarantees alone are worth $13 billion for a single plant.[59]

Even so, some U.S. industry executives, such as Jeffrey Immelt of General Electric, have suggested that loan guarantees are not enough. In an interview with the *Financial Times*, Immelt stated that only "five to ten U.S. nuclear power projects would go ahead unless there was a carbon-pricing framework to create incentives for utilities to build more."[60] In other words, building other electricity generating plants would continue to be more cost-effective than new nuclear power plants, absent carbon pricing.

Just how high would that carbon tax need to be? Estimates vary from $30 a ton of CO_2 to $100 a ton.[61] According to MIT calculations, nuclear generation begins to become competitive with coal when CO_2 is priced at $100 a ton (assuming 85 percent capacity and a forty-year time frame). Yet prices in carbon trading in Europe in the first three years varied from about €30 per metric ton to less than 0.02 per metric ton; in the second round of trading, allowances have been hovering in

59. Doug Koplow, "Government Subsidies to Nuclear Power: A Case Study of UniStar's Calvert Cliffs III reactor," November 5, 2007 draft, available at www.npec-web.org/carbon/DRAFT-20071105-Koplow-NuclearSubsidiesCaseStudy.pdf.
60. "GE Chief Urges Incentives to Fuel Nuclear Switch," *Financial Times*, November 18, 2007.
61. Robert Williams, "Can We Afford to Delay Rapid Nuclear Expansion Until the World Is Safe for It?" Presentation to Bulletin of Atomic Scientists Future of Nuclear Energy Conference, Chicago, November 1–2, 2006, www.ipfmlibrary.org/wil06.pdf.

TABLE 6
Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (85% capacity factor)

Base Case	25-year	40-year
Nuclear	7.0	6.7
Coal	4.4	4.2
Gas (low)	3.8	3.8
Gas (moderate)	4.1	4.1
Gas (high)	5.3	5.6
Gas (high) advanced	4.9	5.1
Reduce Nuclear Costs Cases		
Reduce construction costs (25%)	5.8	5.5
Reduce construction time by 12 months	5.6	5.3
Reduce cost of capital to be equivalent to coal and gas	4.7	4.4

Carbon Tax Cases (25/40 year)

	$50/ tons of carbon	$100/ tons of carbon	$200/ tons of carbon
Coal	5.6/5.4	6.8/6.6	9.2/9.0
Gas (low)	4.3/4.3	4.9/4.8	5.9/5.9
Gas (moderate)	4.6/4.7	5.1/5.2	6.2/6.2
Gas (high)	5.8/6.1	6.4/6.7	7.4/7.7
Gas (high) advanced	5.3/5.6	5.8/6.0	6.7/7.0

Source: Massachusetts Institute of Technology, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, Mass.: Massachusetts Institute of Technology, 2003), 42.

the low €20 per metric ton range (equivalent to $50 per metric ton).[62] A stable, long-term price for carbon is far from assured.

Table 6, taken from the 2003 MIT Study on *The Future of Nuclear Power*, summarizes the costs of electric generation alternatives, along with how particular costs could be reduced for new nuclear power and with a carbon tax. There are a few noteworthy conclusions in the MIT cost summary. First, reducing the cost of capital to be equivalent to coal and gas provides the greatest cost reductions, but it still would not make new nuclear power plants competitive with coal. Likewise, reducing construction costs by 25 percent or reducing construction time by a year would reduce the cost of nuclear power, but not enough to make it competitive with coal. Without these cost reductions, only a carbon price of $200 per ton of CO_2 would make nuclear energy cheaper than coal. With one or more of these cost reductions, nuclear energy

62. Ryan, *Platt's White Paper*, 3

begins to become more competitive at $50 per ton of CO_2. Lowering construction costs, however, may become more difficult to achieve if major expansion occurs. Although many assume that costs will decline as more nuclear plants are built, historical experience has shown the opposite—costs rise. Moreover, bottlenecks in an industry that has atrophied over the last twenty years because of reduced demand may be contributing to rising construction costs.[63] This could affect the United States in particular. As described in more detail below, bottlenecks range from key components and materials to labor and engineering.

Estimates by the Congressional Research Service (CRS) in 2008 suggest similar conclusions: that lowering the cost of capital through loan guarantees or imposing carbon costs could make nuclear energy significantly more competitive in the United States. Table 7 summarizes three of the cases estimated by the CRS—a base case that includes just production tax credits, a government incentives case that includes loan guarantees, and a carbon pricing case.

As table 7 shows, electricity generation using nuclear energy with only a production tax credit is more expensive than all alternatives except solar energy. Adding in loan guarantees makes nuclear energy competitive with natural gas and pulverized coal. Imposing CO_2 allowances pushes up the price of coal-fired electricity significantly above nuclear energy, although natural gas would remain less expensive than nuclear energy.[64]

In sum, new nuclear power plants could become more competitive with significant subsidies and sustained policies that would increase the cost of carbon-based electricity generation. Without aggressive support, their high costs are likely to dampen enthusiasm for major nuclear expansion. An overwhelming challenge in the next ten years will be reducing construction times and costs as engineering, procurement, and construction firms get used to building more of these reactors in new environments. In the United States, the financial risks will continue to dampen enthusiasm on Wall Street for such big projects, and new nuclear power plants will almost certainly continue to be difficult to finance. In developing countries and other countries where public funding is likely, governments will need to assess whether nuclear energy is the least costly way to provide climate-friendly energy compared with the possible alternatives.

63. Lovins and Sheikh, "Nuclear Illusion."

64. The CRS report also included a case that examined sensitivity to higher natural gas prices, which is not included here. For more detail, see Kaplan, "Power Plants."

TABLE 7
Estimated Annualized Cost of Power, 2008 (cents/kWh; 2008 dollars)

Technology	Base Case	Incentives Case	Carbon Pricing Case[a]
Coal: Pulverized	6.3	6.0	10.0
Coal: IGCC[b]	8.2	7.3	11.4
Natural Gas: Combined Cycle	6.1	6.1	7.7
Nuclear	8.3	6.3	8.3
Wind	8.0	7.2	8.0
Geothermal	5.9	5.9	5.9
Solar: Thermal	10.0	10.0	10.0
Solar: Photovoltaic	25.5	25.5	25.5

Source: Stan Kaplan, "Power Plants: Characteristics and Costs," Report for Congress RL34746, Congressional Research Service, November 13, 2008.
[a]The CO_2 allowance price projection was adapted by the CRS from the EIA's "core" case forecast in "Energy Market and Economic Impacts of S.2191, the Lieberman-Warner Climate Security Act of 2007." See the CRS report for more detail. The cost of adding carbon capture and storage to the coal technologies adds about 1 cent per kWh while adding carbon capture and storage to natural gas would add 1.7 cents per kWh.
[b]IGCC = integrated-gasification combined cycle.

Safety and Security

The safety of nuclear power plants has been a paramount concern since the accidents at Three Mile Island in 1979 and Chernobyl in 1986. Both accidents prompted intense reviews of reactor designs and operating protocols. The World Association of Nuclear Operators was created in 1989 to promote industry collaboration on safety, and the Convention on Nuclear Safety entered into force in 1994. Other key agreements adopted after Chernobyl include the Convention on Early Notification of a Nuclear Accident (IAEA INFCIRC/335) and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (INFCIRC/336). In addition, the IAEA implements a program of technical assistance and voluntary assessment of safety for nuclear power programs.

There is little doubt that safety practices have generally improved, and the latest reactors licensed in the United States now feature passive safety systems that do not rely on the actions of reactor operators to shut down systems. Nuclear industry proponents in the United States suggest that the operational record of the country's 104 reactors has been excellent, and point to the high operational effectiveness of the plants, which suggests fewer incident-related shutdowns. Critics point to serious incidents since Three Mile Island, particularly in 2002 at the Davis-Besse plant in Ohio, where corrosive materials burned a football-sized hole in the reactor vessel, as well as to year-long shutdowns of 38 reactors in the United States and to pressures within the Nuclear Regulatory Commission to approve licenses and reduce public scrutiny of safety violations.[65]

The International Nuclear Regulators Association issued recommendations in April 2008 for countries considering nuclear power. The association suggested that these states:

- establish a legal and regulatory framework to govern the safety of nuclear materials and installations that meets the requirements of the Convention on Nuclear Safety on fundamental safety principles and appropriate standards;
- establish an independent nuclear safety regulatory body with authority, competence, and financial and human resources;
- ensure that the independent regulatory body is truly independent; and
- anchor an effective system of nuclear safety regulation and control on a strong national commitment to develop cultures in all relevant organizations and bodies that emphasize nuclear safety as the priority.[66]

It is worth noting that all states currently operating nuclear power plants are parties to the three conventions mentioned above. Encouraging new nuclear states to join the three conventions would provide at least a formal review of compliance with standards, which in the case of the Convention on Nuclear Safety is conducted every three years through national reports.

A wider geographic distribution of reactors (from thirty-one countries to possibly fifty-five or sixty) could introduce physical safety issues. Countries in seismically active regions will need to consider specific improvements designed to withstand earthquakes, and those in coastal areas may need to consider the effects of climate change. One potential effect is the impact of warmer temperatures on cooling water requirements for some kinds of reactors.

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65. See testimony of David Lochbaum, House Select Committee on Energy Independence and Global Warming, March 12, 2008, http://www.ucsusa.org/assets/documents/nuclear_power/20080312-ucs-house-nuclear-climate-testimony.pdf; and David Lochbaum, *Walking a Nuclear Tightrope: Unlearned Lessons of Year-Plus Reactor Outages*, Union of Concerned Scientists, September 2006, available at www.uscusa.org.

66. See the press release at www.nrc.gov/reading-rm/doc-collections/news/2008/08-085.html.

In addition to safety, the security of nuclear power plants has become an increasing global concern since the September 11, 2001, terrorist attacks on the United States. A taped interview on the Al Jazeera network on September 10, 2002, indicated that al-Qaeda operatives had considered an attack on nuclear power reactors. Subsequently, the IAEA created the Nuclear Security Fund, which relies on states' voluntary contributions, and the U.S. Congress mandated that the Nuclear Regulatory Commission reevaluate its criteria for assessing the security of nuclear installations, the so-called design-basis-threat.[67] In 2008 Nuclear Threat Initiative, an international nongovernmental organization, in conjunction with DOE, launched the World Institute for Nuclear Security, which is designed to assist the nuclear industry's efforts to enhance security.

International agreements to enhance the physical protection of nuclear material have been evolving since 2001. Several transport conventions have been updated to extend their purview to nuclear material, including the Convention on the Suppression of Unlawful Acts. The existing Convention on the Physical Protection of Nuclear Material was amended in 2005 to expand its scope beyond the security of nuclear material in transit. The Convention now also covers the physical protection of material in domestic use and contains twelve security principles. Thus far, only seventeen countries have ratified it. Of these, three are states that say they are seeking nuclear power—Algeria, Libya, and Nigeria.[68] Of the twenty-eight states seeking nuclear power, nine have not signed the convention: Bahrain, Egypt, Iran, Jordan, Malaysia, Saudi Arabia, Thailand, Venezuela, and Vietnam.

The nuclear industry understands that the safety and security of nuclear power plants are a critical vulnerability. One accident or terrorist event anywhere in the world would jeopardize investments in nuclear power plants everywhere. The development of safety and security cultures at power plants is imperative, which could be challenging for countries that are just starting down a nuclear path and could take years to mature.[69] Even for advanced nuclear states, efforts to promote

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67. For more information, see Mark Holt and Anthony Andrews, "Nuclear Power Plants: Vulnerability to Terrorist Attack," Congressional Research Report RS21131, www.fas.org/sgp/crs/terror/RS21131.pdf.

68. See www.iaea.org/Publications/Documents/Conventions/cppnm_amend_status.pdf.

69. Cochran, "Contribution of Nuclear Power"; and U.S. Government Accountability Office, *Nuclear Regulatory Commission: Oversight of Nuclear Power Plant Safety Has Improved, but Refinements Are Needed,* GAO Report 06-1029 (Washington, D.C.: U.S. Government Ac-

a security culture distinct from a safety culture are generally in their infancy. The two types of threats are very different; safety is oriented toward preventing accidental and equipment failures, whereas security is focused against purposeful threats. In particular, the promotion of a security culture will require coordination among such varied entities as the power plant licensee, the law enforcement agencies or armed forces that would respond to an incident, and the intelligence services that would help identify threats.

Nuclear Waste

Nuclear reactors unavoidably generate radioactive spent fuel as waste. Spent nuclear reactor fuel can be stored or reused. In both cases, it must first sit in pools of water to cool. It can be stored for several years (depending on the fuel type) in those pools, which are generally at reactor sites, and then either placed in dry casks for further cooling or in a geologic waste repository. Some suggest that dry cask storage is possible for 60 to 100 years. No country yet has opened a geologic repository for its commercial nuclear waste, 50 years after the dawn of commercial nuclear power. Finland and the United States have identified sites, but the future of the Yucca Mountain site in the United States is uncertain. Although a license application for the site was submitted in 2008, the earliest date now for opening Yucca Mountain is estimated by DOE to be 2021. The technical challenges to finding an appropriate site are significant, but in many cases they have been dwarfed by political hurdles.

Several states have recycled their spent fuel. In this process, the plutonium that is produced in the uranium fuel is separated out from the uranium and radioactive fission products. Both the uranium and the plutonium can be reused in reactor fuel; the fission products are classified as high-level waste and must be stored in a geologic repository, preferably in solid form (usually turned into glass in a vitrification process). "Reprocessing"—as it is known—has not been generally

countability Office, 2006). Igor Khripunov has suggested that the groups of countries where raising security standards is urgently needed include transitional societies, countries that lack transparency in their nuclear programs, countries beginning nuclear programs, and countries where the nuclear industry is undergoing reform. See Igor Khripunov, "Nuclear Security Culture: The Case of Russia," presentation at Conference on Managing Nuclear Material Stockpiles in the 21st Century, Oslo, March 3–4, 2005, www.authorstream.com/Presentation/Jolene-22902-Igor-Khripunov-NSC-presentation-Nuclear-Security-Culture-Case-Russia-Definition-Properties-2-IAEA-Global-Concept-Applicabilit-as-Entertainment-ppt-powerpoint.

considered cost-effective compared with storing the fuel (known as the "once-through" fuel cycle). Reprocessing reduces the volume of waste that needs to be stored but produces separated plutonium, a nuclear weapons fuel.[70]

A key question for the future of nuclear energy is how many countries will choose to reprocess their fuel. Some states, such as South Korea, are interested in reprocessing to reduce the volume of their spent fuel. Japan has been reprocessing its spent fuel to both reduce the volume and utilize the plutonium embedded in it as part of an effort to strengthen its energy security. Although there is much evidence that the use of mixed fuel (plutonium and uranium) in reactors is uneconomical, some countries may use it anyway.

Proponents of reprocessing spent nuclear fuel generally point to the fuel's unused energy potential, the future scarcity of uranium, and, more recently, the ability to use such fuel in either plutonium breeder or burner reactors. Breeder reactors make more plutonium than they consume, and theoretically they could greatly enhance energy security; burner reactors have the advantage of burning up more plutonium and therefore have been promoted as a way to rid the world of plutonium stockpiles. No breeder or burner reactors have been commercially deployed, and prototype breeder reactors in France and Japan were shut down due to sodium leaks and fires.

Whether nations are storing spent fuel or recycled waste, adequate physical protection and security against terrorist access are both essential. Even in fuel-leasing schemes, in which spent fuel is shipped back to the original supplier, new nuclear states will still require safe and secure interim storage for fuel as it cools. New nuclear states should be urged to sign the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (INFCIRC/546).

Proliferation

Finally, a defining feature of nuclear energy, in contrast to other electricity sources, is the risk that fissile material, equipment, facilities,

70. Although plutonium produced in a power reactor would not likely be the first choice of a state intent on acquiring a nuclear weapon because of the presence of other plutonium isotopes (for example, Pu-240) that tend to poison the nuclear chain reaction, so-called reactor-grade plutonium can be used in nuclear weapons, and the United States demonstrated this in its nuclear tests.

and expertise can be misused to develop nuclear weapons. No other type of electricity-generating plant requires international inspections to detect diversion of material. Within the nonproliferation community, views divide about whether power reactors pose as significant a risk as research reactors, which have been used in a few states to produce plutonium for weapons. Some observers point out that power reactors historically have not been used to produce plutonium for nuclear weapons, while others suggest that any power reactor can be operated to make weapons-usable plutonium. The only question is where to draw the line in mitigating the risk.

Everyone agrees, however, that uranium enrichment—which is necessary to produce the fuel for the light-water reactors that constitute 80 percent of all power reactors in operation—and spent-fuel reprocessing pose particular risks because those separation processes produce weapons-usable material without radiation barriers. If a country has enrichment and reprocessing capabilities, or weapons-usable fissile material stockpiled, and chooses to leave the Nuclear Nonproliferation Treaty, it could be a matter of weeks before a nuclear weapon could be produced.

A major expansion in nuclear power reactors does not necessarily mean the spread of other fuel cycle capabilities such as uranium enrichment and spent-fuel reprocessing. At this juncture, however, it appears likely that such capabilities will spread. Agreement among suppliers to rein in the expansion of these sensitive nuclear technologies seems to be unraveling, and potential recipients are loath to accept new nonproliferation restrictions on their access to technology.

Resolving Nuclear Energy's Challenges?

Virtually all the challenges described above could be exacerbated by a massive expansion of nuclear energy. Some analysts argue that some of these challenges would have to be met directly before such an expansion could occur. For example, the 2003 MIT study suggested that an expansion of 1,000 or 1,500 GW would require resolving at least three issues: Costs would have to be reduced (and a carbon tax would make nuclear energy more appealing); best practices would need to be adopted for operations and maintenance; and the once-through fuel cycle (that is, storing spent fuel, rather than reprocessing it for use in future fuel) would need to be retained. In addition, the MIT study suggested that not only would the United States need to provide leadership, but Asia would also need to continue its nuclear expansion, Europe would need to reverse some of its nuclear decline, and other states would need to agree to deploy nuclear power reactors. Public opinion would also need to support nuclear energy for climate change.

Pacala and Socolow maintained in their 2004 *Science* article that the pace of reactor construction envisioned would require restoring public confidence in safety and waste disposal and crafting international security agreements governing uranium enrichment and plutonium recycling. The IEA noted that "major policy and regulatory hurdles . . . may take considerable time to resolve," for the rapid expansion of nuclear energy in its 450 Stabilization Scenario. In the IEA's more far-reaching scenarios (ACT and Blue), analysts noted that public acceptance could be improved through the development of Generation IV reactors, which could reduce costs, minimize waste, and improve safety. Small and medium-sized reactors should be developed (which will likely await commercialization until after 2030), and wider political and public acceptance should be nurtured through public information campaigns. Workforces would need to be developed on an urgent basis, and proliferation-resistant fuel systems would need to be developed.[71] However, all these steps would take many years to implement, which runs counter to the imperative to act now on climate change.

GLOBAL CAPACITY FACTORS

Assuming that all these significant hurdles could be surmounted, could the nuclear industry infrastructure sustain the kinds of expansion envisioned? In the last twenty years, there have been fewer than ten new reactor construction starts in any given year worldwide. Table 8, reproduced from the Power Reactor Information System of the IAEA, shows annual construction starts and connections to the grid from 1955 to 2006.

A 2007 Keystone Center report pointed out that to build 700 GW of nuclear power capacity "would require the industry to return immediately to the most rapid period of growth experienced in the past (1981–1990) and sustain this rate of growth for 50 years."[72] Even China's command economy is only envisioning building four reactors a year through 2020. Some analysts are skeptical that this is possible, and that such growth could be accomplished with manufacturing safety standards that others would find acceptable.

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71. International Energy Agency, *Energy Technology Perspectives* (Paris: International Energy Agency, 2008), 137.

72. Keystone Center, *Nuclear Power Joint Fact-Finding*, 27.

TABLE 8
Annual Construction Starts and Connections to the Grid, 1955 to 2006

Year	Construction Starts		Connections to the Grid		Reactors in Operation	
	Units	MW(e)	Units	MW(e)	Units	MW(e)
1955	8	352			1	5
1956	5	577	1	50	2	55
1957	13	1747	3	134	5	189
1958	6	434	1	50	6	239
1959	7	906	5	238	11	479
1960	11	910	4	452	15	931
1961	7	1384	1	15	16	946
1962	7	1237	9	893	25	1839
1963	5	1600	9	457	33	2266
1964	9	2694	8	1036	40	3227
1965	9	3144	8	1679	48	4908
1966	14	6878	8	1371	55	6274
1967	23	14788	11	2093	64	8319
1968	32	22955	6	1051	68	9348
1969	15	11551	10	3664	78	13047
1970	34	23410	6	3472	84	16561
1971	13	8056	15	7243	99	23934
1972	29	22485	15	8517	113	32571
1973	29	24286	19	11571	132	43745
1974	27	24380	26	17433	154	61156
1975	32	31020	15	10340	169	70580
1976	33	31360	18	13680	186	84116
1977	19	16691	17	12358	200	96443
1978	14	13030	20	16247	219	111882
1979	25	22230	8	6945	225	117951
1980	20	19355	21	15579	245	133122
1981	15	14204	23	20570	267	153937
1982	14	15726	19	15689	284	168486
1983	9	7597	23	19006	306	187824
1984	7	7095	33	31788	336	218516
1985	13	11066	33	31481	363	245752
1986	6	5196	27	27304	389	270932
1987	8	7737	22	22231	407	293927
1988	5	5881	14	13912	416	305298
1989	6	4053	12	10687	420	312087
1990	4	2459	10	10481	416	318386
1991	2	2291	4	3668	415	321974
1992	3	3126	6	4806	418	325045
1993	4	3602	9	8997	427	333945
1994	2	1367	5	4251	429	336952
1995			4	3328	434	341429
1996	1	610	6	7029	438	347327
1997	5	4466	3	3679	433	347625
1998	3	2096	4	3074	430	344166
1999	4	4594	4	2787	432	347486
2000	6	5363	6	3111	435	349852
2001	1	1304	3	2733	438	352753
2002	5	2440	6	5059	439	357438
2003	1	202	2	1644	437	359889
2004	2	1336	5	4785	438	364807
2005	3	2900	4	3852	441	368239
2006	4	3320	2	1490	435	369682

Source: IAEA Power Reactor Information System Database, 2008.

A significant expansion will narrow bottlenecks in the global supply chain, which today include ultra-heavy forgings, large manufactured components, engineering, and craft and skilled construction labor. All these constraints are exacerbated by the lack of recent experience in construction and by aging labor forces. Though these may not present problems for limited growth, they will certainly present problems for doubling or tripling reactor capacity.[73]

In the United States, the problems may be particularly acute. The chief operating officer of Exelon told a nuclear industry conference in early 2008 that the lack of any recent U.S. nuclear construction experience, the atrophying of U.S. nuclear manufacturing infrastructure, production bottlenecks created by an increase in worldwide demand, and an aging labor force could all prove to be constraints on major expansion.[74]

Lack of construction experience translates into delays, which mean much higher construction costs. For example, AREVA has had trouble pouring concrete for its new reactors in Olkiluoto, Finland, and Flammanville, France. The eighteen-month delay caused by faulty construction of Olkiluoto-3 was estimated to cost €1.5 billion in overruns in a project with a fixed cost of €3 billion.[75] This was before a fire occurred in July 2008 that probably caused further delays.[76] In an analysis for a nuclear industry conference, the consulting firm Booz Allen Hamilton prioritized fifteen different risks in new reactor construction. The most serious ones entailed engineering, procurement and construction performance, resource shortages, and price escalation.[77]

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73. According to a Department of Energy report, "the necessary manufacturing, fabrication, labor, and construction equipment infrastructure is available today or can be readily developed to support the construction and commissioning of up to eight nuclear units during the period from 2010 to 2017." U.S. Department of Energy, "DOE NP2010 Nuclear Power Plant Construction Infrastructure Assessment," October 2005.

74. Christopher M. Crane, chief operating officer, Exelon Generation, "The Challenge of Growth in Nuclear Power: It Ought to Work, but Will It?" Presentation to Platt's Fourth Annual Nuclear Energy Conference, Bethesda, Md., February 5–6, 2008.

75. Ryan, *Platt's White Paper*.

76. Mycle Schneider, "2008 World Nuclear Industry Status Report: Western Europe," *Bulletin of Atomic Scientists*, September 18, 2008, www.thebulletin.org/web-edition/reports/2008-world-nuclear-industry-status-report/2008-world-nuclear-industry-status-re-1.

77. Other risks included delivery delays, materials not made to specifications, site-related issues, safety-related delays, labor productivity, Nuclear Regulatory Commission delays, the rolling back of incentives, changes in design, late engineering, balance sheet exposure, and project financing availability. Presentation by Tom Flaherty, Booz Allen Hamilton, Platt's Fourth Annual Nuclear Energy Conference, Bethesda, Md., February 5–6, 2008.

The atrophying of nuclear manufacturing infrastructure is significant not only in the United States but also worldwide, except in Japan. The ultraheavy forgings for reactor pressure vessels and steam generators are the most significant chokepoint. Japan Steel Works (JSW) is currently the only company worldwide with the capacity to make the ultralarge forgings (using 600-ton ingots) favored by new reactor designs. Other companies—such as Sfarsteel (formerly Creusot Forge) in France and Doosan Industry in South Korea—have smaller capacities. The purchase of Creusot Forge by AREVA in 2005 means that Creusot's former customers reportedly are shifting to JSW, lengthening the two-year waiting list. According to *World Nuclear Industry Status 2007*, AREVA has stated that

> . . . the annual capacity at the Chalon plant is limited to 12 steam generators plus "a certain number of vessel heads" and small equipment, or the equivalent of between 2 and 2.5 units per year, if it did manufacture equipment for new plants only. In reality, the Chalon capacities are booked out, in particular for plant life extension measures—steam generator and vessel head replacement—also for the U.S. market.
>
> In July 2007 AREVA announced that the heavy forgings it had ordered in 2006 from JSW for a US-EPR had begun to arrive at its Chalon facility. AREVA claims that the order of forgings made the company the only vendor to have "material in hand to support certainty of online generation in 2015."[78]

Recently, AREVA negotiated with JSW to ensure that its orders through 2016 would be filled. AREVA also reportedly invested in JSW to help with the costs of expansion. According to JSW officials, it now produces 5.5 sets of forgings per year; this will expand to 8.5 sets in 2010. Even then, nuclear forgings at JSW compete with orders for forgings and assembly from other heavy industries—for example, oil and gas industries, which can be more profitable.

In time, new suppliers are likely to emerge to support nuclear expansion. According to JSW officials, the availability of alternative ultraheavy forging supply is not necessarily a question of manufacturing capabilities but rather of business decisions to focus on more profitable industrial projects. Currently, Toshiba reportedly can produce one nuclear steam supply system (the "nuclear" part of the reactor that includes the reactor pressure vessels, moisture separator/reheater, steam generator, steam turbine generators, fuel assemblies, and so on) per year,

78. Mycle Schneider with Antony Froggatt, *World Nuclear Industry Status 2007* (Brussels: Greens-EFA Group in the European Parliament, 2007), 15, www.greens-efa.org/cms/topics/dokbin/206/206749.pdf.

and Doosan Heavy Industries in South Korea can produce one and a half systems per year.[79] Doosan will assemble reactor pressure vessels for the four Westinghouse reactors (AP-1000s) under construction in China. Russia's Uralmash-Izhora Group (or OMZ) reportedly stated in October 2007 that it would double its production of large and ultralarge forgings for the VVER-440 and VVER-1000 pressurized water reactors from two to four per year. However, it is not clear whether these reactors have certification from the American Society of Mechanical Engineers, which can take five to ten years and is desirable for exports.[80]

A few factors will influence how quickly and successfully nuclear reactor construction capacity could expand: technical challenges, quality assurance and certification requirements, and the uncertainty of new business. In forging, there are considerable technical challenges in melting, forging, heat treatment, and machining operations that new entrants into the ultralarge forging business would need to overcome.[81] Quality assurance could play an important role in whether or not new ultralarge forging capabilities succeed. According to Nuclear Regulatory Commission chairman Dale Klein, quality assurance by Chinese firms in producing other nuclear-related components has been a concern.[82]

Finally, the nuclear industry appears wary of expanding too quickly, lest expansion not proceed as planned. JSW suffered financially ten years ago when Germany canceled its orders for new nuclear power plants.[83] China was set to open new ultraheavy forging plants in 2008, to produce possibly as many as six sets per year. If its own production takes up four per year, this could allow the Chinese to supply two others for reactor projects abroad through 2020. In the meantime, it is possible to

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79. U.S. Department of Energy, *DOE NP2010 Nuclear Power Plant Construction Infrastructure Assessment* (Washington, D.C.: U.S. Government Printing Office, October 21, 2005), 4-3.

80. Miles Pomper, "The Russian Nuclear Industry: Status and Prospects," Nuclear Energy Futures Paper 3, November 2008, available at www.cigionline.org.

81. Correspondence with Yoshitaka Sato, general manager, Forgings and Castings Export Sales, Japan Steel Works, Ltd., May 8, 2008. Some of the challenges in melting operations include minimizing the chemical composition of impurities, achieving sufficient uniformity of chemistry in the ingots, and avoiding cracks. Sato also noted that "very sophisticated documentation and quality-control systems by experienced engineers and inspectors in the English language are mandatory to provide a final product."

82. Mark Hibbs, "Non-Transparent Lines of Command Adds to Concerns about Chinese Equipment," *Inside NRC*, April 28, 2008, 1, 13.

83. Charles Ferguson, "How Not to Build Nuclear Reactors," *Bulletin of Atomic Scientists*, September/October 2008, 26.

use smaller-capacity forgings, but this means more components, with more weld seams, and therefore will require more safety inspections. Here again, time is money, and one estimate is that the cost of shutdowns for inspections or other reasons is $1 million a day.[84]

In addition to the major nuclear reactor vendors, supporting industries will also either need to be rebuilt or recertified to nuclear standards. In the United States, the decline of supporting industries is significant. In the 1980s, the United States had 400 nuclear suppliers and 900 holders of N-stamp certificates from the American Society of Mechanical Engineers.[85] Today, there are just 80 suppliers and 200 N-stamp holders.[86] In addition, certain commodities used in reactor construction may also present supply problems, such as alloy steel, concrete, and nickel. The costs of these inputs, according to Moody's, have risen dramatically in recent years.

Labor Force Issues

Labor force constraints are likely to be felt worldwide. In the United States, aging workforces at nuclear power plants present a problem. For example, at Florida Power and Light Company, 40 percent of current nuclear power plant workers are eligible to retire in the next five years.[87] This is slightly higher than the national average of 35 percent (or 19,600 workers) eligible to retire. The Nuclear Regulatory Commission confronts a similar challenge.

In France, which has been steadily building reactors, the situation appears to be no better. At Électricité de France (EDF), the national utility, 40 percent of current staff in reactor operation and maintenance will retire by 2015. EDF hopes to hire 500 engineers annually.[88] The French reactor builder AREVA has been active not just in hiring engi-

84. Comment by Philip Tollerini of AREVA, February 8, 2008.
85. Jim Harding, "Seven Myths of the Nuclear Renaissance," Paper presented at the Conference on the 50th Anniversary of the Euratom Treaty Brussels, March 7–8, 2007, www.nirs.org/nukerelapse/neconomics/jimharding382007.pdf.
86. The Nuclear Energy Institute notes that some of the decline in N-stamp holders is due to consolidation of companies, but nonetheless it is encouraging firms to get recertified.
87. Comments by Art Stall, senior vice president and chief nuclear officer of Florida Power and Light Company to American Nuclear Society's 2007 Annual Meeting, quoted by Schneider and Froggatt, *World Nuclear Industry Status Report 2007*. Stall also noted that only 8 percent of the current nuclear plant workforce is under thirty-two years old.
88. Ibid, 12.

neers (400 in 2006 and 750 in 2007) but also in industrial workforce development programs in the United States.

Competition From Other Electricity and Construction Projects

According to a 2008 Bechtel estimate, if electricity demand grows in the United States 1.5 percent each year, and the energy mix remains the same, the United States would have to build 50 nuclear reactors, 261 coal-fired plants, 279 natural gas–fired plants, and 73 renewables projects by 2025 to keep up. All of these will require craft and construction labor. According to DOE, only a portion of the construction labor used to build fossil fuel–fired plants would have the skills necessary to build nuclear power plants.[89]

In addition to competing with other electricity projects, nuclear power construction competes with other large investment projects for labor and resources, particularly oil infrastructure. In the United States, rebuilding from Hurricane Katrina and big construction projects in Texas will continue to place pressure on construction labor forces. A Bechtel executive recently stated that the United States will face a skilled labor shortage of 5.3 million workers in 2010, which could rise to a shortage of 14 million by 2020. Adding to this is the retirement of baby boomers, and much slower growth in the number of college graduates.[90] Building a nuclear power plant in the United States requires 1,400 to 2,300 construction workers for four or more years. And the permanent labor force of a nuclear power plant numbers between 400 and 500.

On the front end of the fuel cycle—uranium exploration, mining, and milling—similar pressures are being felt, including a loss of industry knowledge, increased regulations and difficulties in mine development, greater risk for investors, and a shortage of skilled workers.[91]

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89. U.S. Department of Energy, "DOE NP2010 Nuclear Power Plant Construction Infrastructure Assessment," 6–14.

90. Brian Reilly, principal vice president, Bechtel, "Challenges of Construction Labor for New Builds," Presentation to Platt's Fourth Annual Nuclear Energy Conference, Bethesda, Md., February 5–6, 2008.

91. G. W. Grandey, the chief executive of Cameco, enumerated several of the challenges in a keynote speech for an international symposium on uranium production in 2005. International Atomic Energy Agency, "Uranium Production and Raw Materials for the Nuclear Fuel Cycle: Supply and Demand, Economics, the Environment, and Energy Security," in *Proceedings from an International Symposium, Vienna, June 20–24, 2005* (Vienna: International Atomic Energy Agency, 2005), 23.

It is likely that these supply issues could resolve themselves within a decade, with sufficient government policies to reverse some of the decline. U.S. nuclear firms have suggested a menu of options, including delays in taxing new domestic nuclear industry until national policy objectives for nuclear manufacturing are met; establishing a nuclear workforce program; and ensuring American access to other nuclear markets.[92] The U.S., French, and British nuclear industries are engaged in several efforts to promote growth in the nuclear workforce. In the end, only a major expansion could help promote nuclear energy as a growth industry that would attract labor and give nuclear suppliers the confidence to expand. An expansion overseas, however, could siphon off some of these resources.

WHERE MIGHT NUCLEAR ENERGY EXPAND?

Tripling or quadrupling nuclear capacity to meet climate change imperatives would likely mean a wide distribution of nuclear power plants around the globe. Such a distribution would have particular implications for nuclear proliferation. However, projected distributions of nuclear energy through 2050 are extremely speculative. The industry itself does not engage in such projections, and countries that set nuclear energy production goals have a history of widely missing long-range targets, such as China and India. Nonetheless, discussion about climate change has prompted many states to consider options for energy production at least to 2030. The following discussion describes states' plans for nuclear expansion to 2030 and considers a hypothetical distribution of nuclear energy for 2050, based on the 2003 MIT study.[93]

92. See, for example, John A. Fees, president and chief operating officer, BWX Technologies, Inc., "Reviving America's Industrial Base," *NEI Nuclear Policy Outlook* (Nuclear Energy Institute), October 2006, 5–8.

93. Massachusetts Institute of Technology, *Future of Nuclear Power*, made projections of per capita electricity growth rates, assuming states would place a priority on reaching the benchmark 4,000 kWh per capita consumption level that is the dividing line between advanced and developing economies, according to the Human Development Index. Based on a pattern of electricity consumption, the study then estimated the proportion of nuclear power generating electricity, taking into account current nuclear power deployment, urbanization, stage of economic development, and energy resource base.

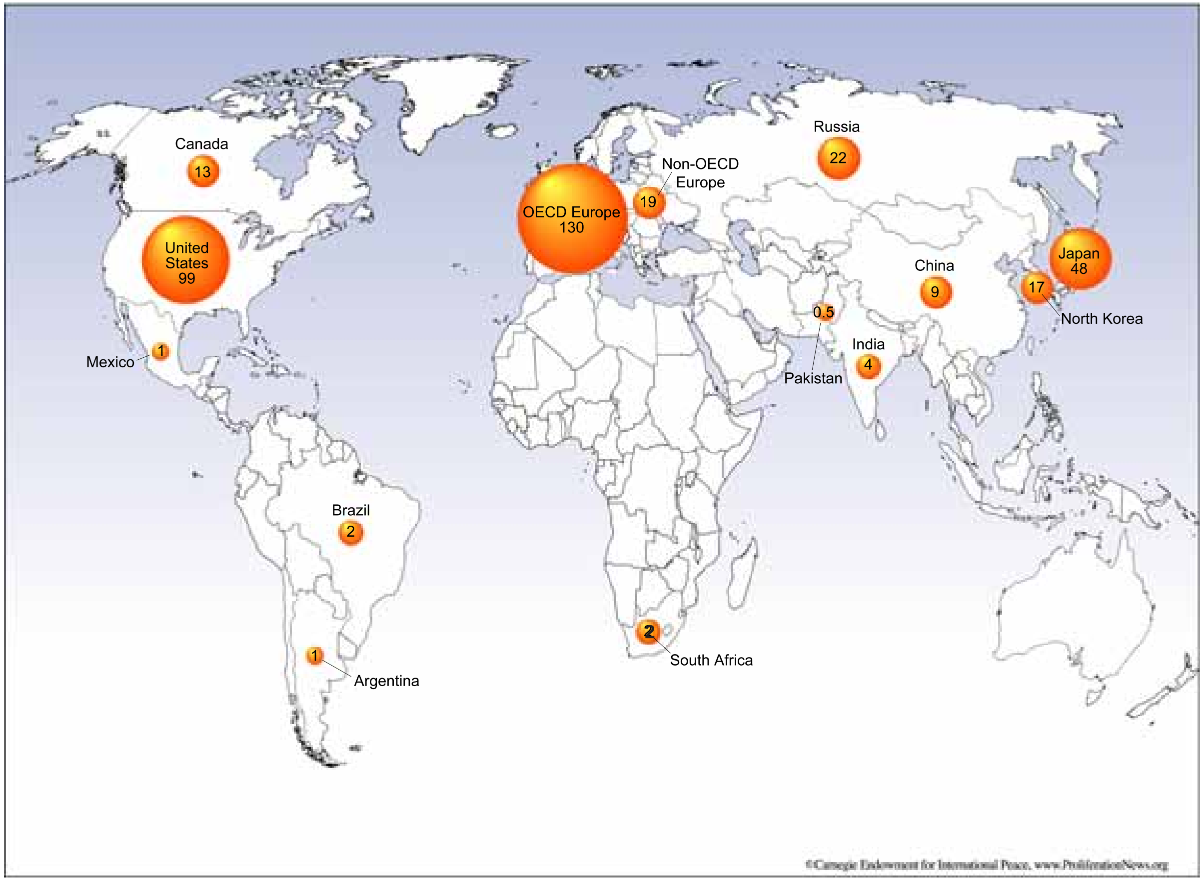
The Current Distribution of Nuclear Energy

Most nuclear power plants are concentrated in three geographic regions: North America, Europe, and Asia (see figure 5). Within those regions, the United States, France, and Japan have more than half of all total capacity (479 nuclear power reactors with 371 GWe capacity). Of the thirty-one states with nuclear power, seven are developing countries—Argentina, Brazil, China, India, Pakistan, South Africa, and Taiwan.

To provide fuel for those reactors, industrial concerns run commercial enrichment plants in eight different countries. Commercial spent-fuel reprocessing capabilities are located in five countries (see figure 6).

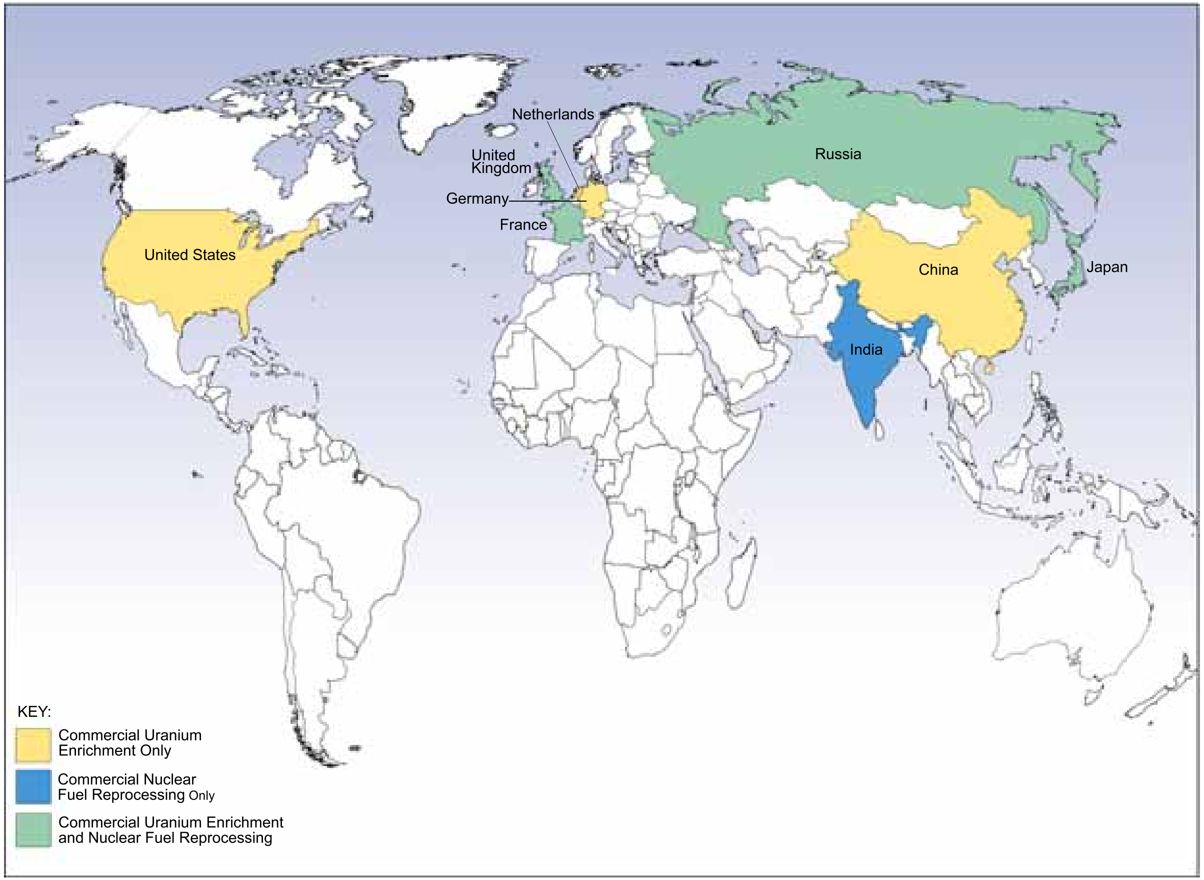
Much of the recent growth in nuclear capacity has been in Asia, and this trend is likely to continue. But nuclear power could become more widely distributed if countries that have announced an interest in nuclear energy follow through on their plans. This could mean spreading nuclear power to perhaps an additional two or three dozen countries, including many more developing states.

FIGURE 5
Reactor Capacities, 2008



Note: There are 479 nuclear power reactors with a capacity of 371 gigawatts electric.

FIGURE 6
Location of Commercial Uranium Enrichment Plants and Reprocessing Plants for Spent Fuel, 2008



Proposed Expansion

Figure 7 shows the more than twenty-five states that have expressed interest in nuclear power. Some of these countries (shown with darker shading) have more detailed plans than others, but the IAEA has cautioned that states just beginning to embark on the path toward nuclear energy can expect at least fifteen years to elapse before their first plant begins operation. They will need this time to develop the necessary physical and intellectual infrastructures to operate nuclear power plants safely and securely. If these states are serious about their plans and could develop the necessary expertise, regulatory systems, and infrastructure, the global nuclear energy capacity could double by 2030. Figure 8 shows approximately what the global capacity might be if these plans were to come to fruition. In some cases, the plans are not very likely to materialize.

The U.S. State Department believes that about a dozen countries are "giving serious consideration to nuclear power in the next ten years."[94] Of this dozen, several have plans to build nuclear reactors that do not now have nuclear power, including Azerbaijan, Belarus, Egypt, Indonesia, Kazakhstan, Turkey, and Vietnam. Turkey is the furthest along in its plans, according to the IAEA. Nineteen countries with longer-term plans, according to the State Department, include Algeria, Bahrain, Chile, Georgia, Ghana, Jordan, Kuwait, Libya, Malaysia, Morocco, Namibia, Nigeria, Oman, Qatar, Saudi Arabia, Syria, the United Arab Emirates, Venezuela, and Yemen.[95] Table 9 lists the countries that have declared an interest in nuclear power, arranged according to the earliest target dates for completion.

At least ten countries listed in table 9 are among the top thirty CO_2 emitters worldwide. Half of these are oil-producing countries and use oil and natural gas to generate their electricity. For example, Egypt relies on oil and gas for three-quarters of its electricity generation, and Saudi Arabia relies entirely on oil and gas. Although these countries may desire to reduce their carbon emissions, a more pressing factor driving nuclear energy enthusiasm is likely to be record-high prices for

94. International Security Advisory Board, U.S. Department of State, "Proliferation Implications of Global Expansion of Civilian Nuclear Power," April 2008, www.state.gov/documents/organization/105587.pdf.

95. The State Department report also included Australia in this category, but the list was prepared in 2007, before Australian elections put a Labor government in power that currently has no plans for nuclear power.

FIGURE 7
Proposed New Nuclear States, 2008

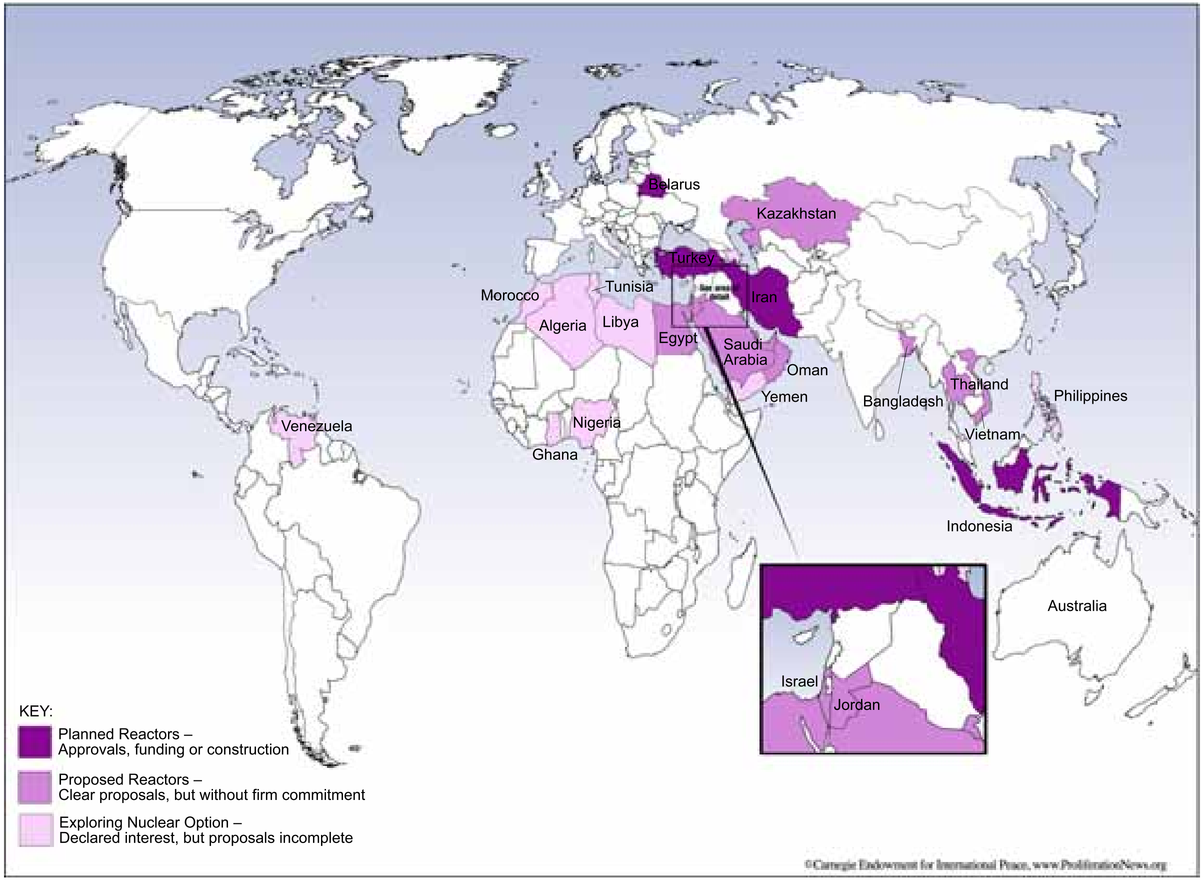
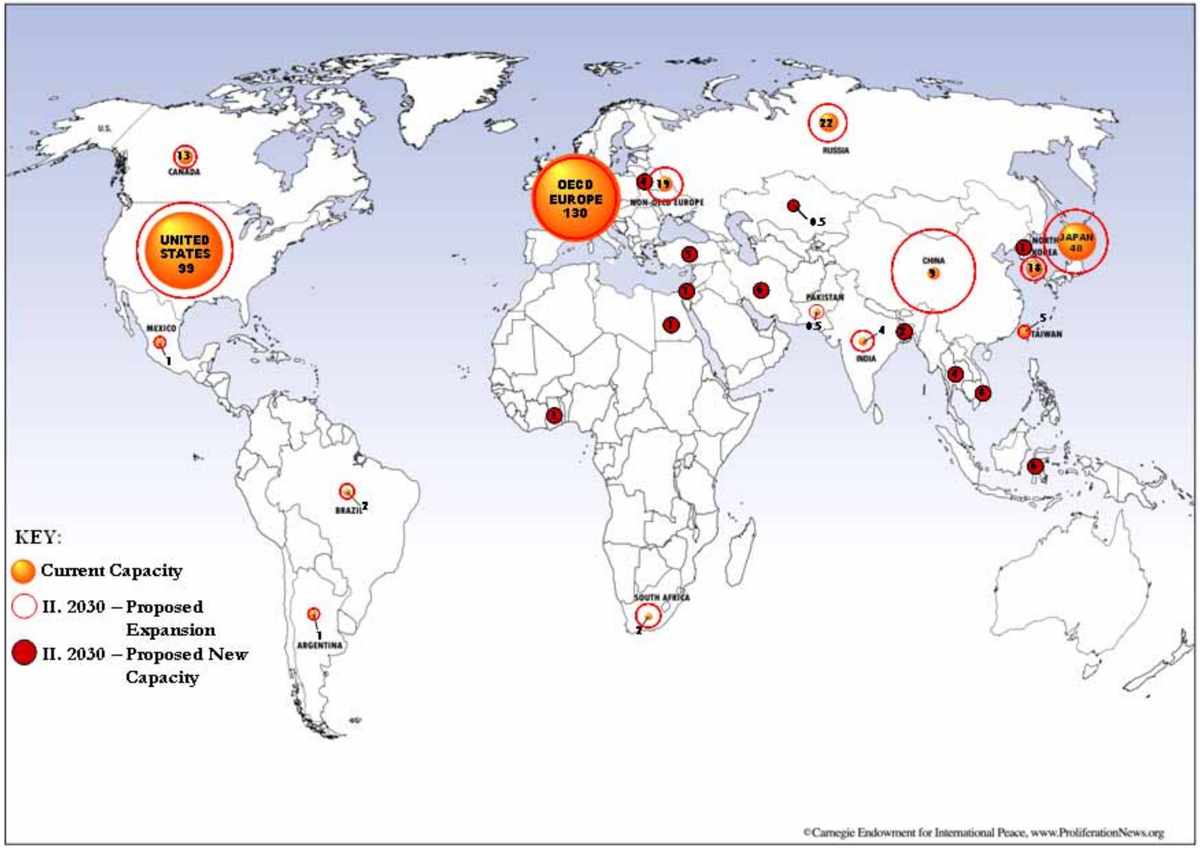


FIGURE 8
Expansion in Global Reactor Capacity According to States' Plans



Note: This figure is not a projection but a scenario, based on official statements by countries. Country statements were taken at face value, and these do not necessarily correlate to any measurable indicators (such as GDP growth or electricity demand).

TABLE 9
States with an Interest in Nuclear Power: Energy, CO2 Emissions & Development

Country	GWe	Target Date	Coal	Energy Mix*		Renewable	CO2** Emissions	Human Development Index	Failed States Index
				Oil	Gas				
Turkey	3-4?	2014	26%	35%	27%	12%	**226/3.2**	M	
Bangladesh	2	2015	2	19	45	35	37/.3	M	12
Jordan	0.5	2015	0	79	20	1	16/3	M	
Egypt	1	2015	2	50	45	4	**158/23**	M	40
Morocco	?	2016	32	60	3	4	41/1	M	
Azerbaijan	1		0	39	59	2	31/4	M	
Belarus	4	2016	2	28	64	5	65/6	H	53
Indonesia	6	2016	14	37	17	32	**378/2**	M	60
Iran	6	2016	1	48	51	1	**433/6**	M	
UAE	3	2017	0	28	72	0	**149/34**	H	
Vietnam	8	2020	16	24	10	50	99/6	M	
Thailand	4	2020	11	46	26	17	**268/4**	M	
Israel	1		39	51	6	4	71/10	H	58
Saudi Arabia	?		0	64	36	0	**308/14**	H	
Oman	?		0	33	67	0	31/14	H	
Qatar	?		0	16	84	0	53/80	H	
Bahrain	?		0	23	77	0	17/24	H	
Kuwait	?		0	67	34	0	99/37	H	
Kazakhstan	0.6	2025	53	15	34	1	200/13	M	
Nigeria	4	2025	0	14	8	79	114/1	L	18
Algeria	5?	2027	.2	32	66	.3	**194/6**	M	
Ghana	1	2030	0	29	0	71	7/.3	L	
Tunisia	0.5	2030	0	50	37	14	23/2	M	
Yemen	?	2030	0	99	0	1	21/1	L	21
Philippines		2050	14	35	6	45	81/1	M	59
Libya	1	2050	0	73	27	1	60/9.3	H	
Venezuela	4?	2050	.1	50	38	12	**173/7**	M	
Malaysia		2050	10	43	42	5	**177/8**	H	

Source: Human Development Report 2007/2008 for HDI index, total primary energy supply figures and 2004 CO_2 emissions; World Nuclear Association for states' nuclear plans, including target dates.

* = percentage of each energy sources of total primary energy supply (not electricity); ** = 2004 CO_2 equivalent emissions, millions of tons. Second number is tons of emissions per capita. Numbers in bold indicate state is among the top 30 CO_2 emitter. The Failed States Index is from 2008 *Foreign Policy* Special Report.

oil and gas. Oil-producing states are likely motivated by lost export revenues from using oil and gas domestically.[96]

Many of the states interested in nuclear power anticipate large growth in electricity demand. Others may simply be jumping on the nuclear bandwagon, either to make a national statement about capabilities or to take advantage of what they may perceive as incentives from advanced nuclear states. Efforts by France, the United States, and Russia to promote nuclear energy have generated significant interest. Recent nuclear cooperation agreements—between France and the United Arab Emirates, Libya, Algeria, and Morocco; between the United States and Turkey, India, Jordan, the United Arab Emirates, and, potentially, Bahrain; and between Russia and Algeria, Armenia, Myanmar, Venezuela, and Vietnam—have contributed to the more widespread perception of the attractiveness of nuclear power.

The nuclear industry knows that interest in nuclear power does not always culminate in contracts or in the completion of projects.[97] Public opposition in the past has played a significant role, but so has a lack of financial wherewithal. These are two important factors in getting projects completed, but there are many other prerequisites for successful operation of nuclear power in any nation. These include having appropriate legal and regulatory frameworks; national accounting and international safeguards for nuclear material; and programs for nuclear waste, nuclear safety, security, physical protection, and radiation protection. Table 10 lists the current status of participation in international legal frameworks by states that have expressed an interest in nuclear power.

Signing on to international conventions that govern nuclear safety, security, and liability would be useful steps but are not sufficient to meet the myriad requirements for the safe and secure development of

96. The United Arab Emirates described burning liquids to produce electricity as "logistically viable, [but] evaluation of this option revealed that a heavy future reliance on liquids would entail extremely high economic costs, as well as a significant degradation in the environmental performance of the United Arab Emirates' electricity sector." See United Arab Emirates, Policy of the United Arab Emirates on the Evaluation and Potential Development of Peaceful Nuclear Energy, 2008, http://www.gulfnews.com/images/08/04/20/nuclear_policy.pdf.

97. In the past, at least thirteen countries began power reactor projects and subsequently canceled them, some because of public opposition and others because of lack of financing. Three of those countries are now considering nuclear power again—Bangladesh, Italy, and the Philippines. A few other countries that did not get beyond bids, such as Turkey and Egypt, will try to move forward again.

TABLE 10
Participation in International Agreements Related to Nuclear Safety, Security & Safeguards by States with an Interest in Nuclear Power

Country	GWe	Target Date	Safeguards		Safety CNS	Security CPPNM	Waste**	Liability (Vienna Convention or CSC)
			CSA	AP				
Turkey	3-4?	2014	Y	Y	Y	Y	N	N
Bangladesh	2	2015	Y	Y	Y	Y	N	N
Jordan	.5	2015	SQP	Y	N	N	N	N
Egypt	1	2015	Y	N	Y	N	N	VC
Morocco	?	2016	Y	N	N	Y	Y	VC*
Azerbaijan	1		Y	Y	N	Y	N	N
Belarus	4	2016	Y	N	Y	Y	Y	VC
Indonesia	6	2016	Y	Y	Y	Y	N	CSC*
Iran	6	2016	Y	N	N	N	N	N
UAE	3	2017	SQP	N	N	Y	N	N
Vietnam	8	2020	Y	N	N	N	N	N
Thailand	4	2020	Y	N	N	N	N	N
Israel	1		N	N	N	Y	N	VC*
Saudi Arabia	?		SQP	N	N	N	N	N
Oman	?		N	N	N	Y	N	N
Qatar	?		SQP	N	N	Y	N	N
Bahrain	?		SQP	N	N	N	N	N
Kuwait	?		SQP	Y	Y	Y	N	N
Kazakhstan	.6	2025	Y	Y	N	Y	N	N
Nigeria	4	2025	Y	Y	Y	Y	Y	VC
Algeria	5?	2027	Y	N	Y	Y	N	N
Ghana	1	2030	Y	Y	N	Y	N	N
Tunisia	.5	2030	Y	N	Y	Y	N	N
Yemen	?	2030	SQP	N	N	Y	N	N
Philippines		2050	Y	N	N	Y	N	VC, CSC*
Libya	1	2050	Y	Y	N	Y	N	N
Venezuela	4?	2050	Y	N	N	N	N	N
Malaysia		2050	Y	N	N	N	N	N

*= signed, not ratified. ** = Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (INFCIRC/546)
AP = Additional Protocol (INFCIRC/540); CNS = Convention on Nuclear Safety; CPPNM = Convention on the Physical Protection of Nuclear Material; CSA = Comprehensive Safeguards Agreement (INFCIRC/153); CSC = Convention on Supplementary Compensation

nuclear power. Human resources are especially critical, particularly in developing a safety and security culture. With so many developing countries considering nuclear power for the first time, the IAEA is actively providing guidance, review, and support to help them build the infrastructure for nuclear energy. The IAEA has identified nineteen issues that should be addressed in building this infrastructure and has stressed that nuclear energy is a 100-year commitment, from development to decommissioning.[98] Most developing countries would need to import reactors and, possibly, the staff to operate them. Potential suppliers will choose where to engage, based on the certainty of payment, volume of work, and political stability and security, among other criteria.

The IAEA estimates that about fifteen years will elapse between a policy decision to develop nuclear power and the operation of a first plant.[99] By 2020, the IAEA estimates that power plant construction could begin in eight countries, and possibly in fifteen more by 2030.[100] Although there is a growing recognition that many of these developing countries would be better served by small and medium-sized reactors (from 300 to 700 MWe), because of the capacities of their electrical grids, there will be few available options for states to purchase smaller reactors in that time frame. Westinghouse has built 600-MWe reactors in the past and has licensed the AP-600, but officials say there are no plans to market it. China has exported 300-MWe reactors, and India has built smaller reactors (from 160 to 500 MWe) and has expressed the desire to get into the export market. Unfortunately, Indian reactors could pose greater proliferation risks, for a variety of reasons.[101] In the

98. The full list is establishing a country's national position, legal and regulatory frameworks, financing, safeguards, energy planning, nuclear waste, nuclear safety, stakeholder involvement, management, procurement, radiation protection, human resource development, security and physical protection, the nuclear fuel cycle, environmental protection, sites and support facilities, the electrical grid, and industrial involvement. See International Atomic Energy Agency, *Milestones in the Development of a National Infrastructure for Nuclear Power*, http://www-pub.iaea.org/MTCD/publications/PDF/Pub1305_web.pdf.

99. See International Atomic Energy Agency, *Roles and Responsibilities of Vendor Countries and Countries Embarking on Nuclear Power Programmes to Ensure Long-Term Safety*, summary of a workshop organized by the IAEA Division of Nuclear Installation Safety in July 2008, www.iaea.org/NewsCenter/News/2008/nuclnewcomers.html.

100. Akira Omoto, director, Division of Nuclear Power, International Atomic Energy Agency, briefing, "IAEA Support to Infrastructure Building in Countries Considering the Introduction of Nuclear Power," 2008.

101. India has built pressurized, heavy-water-moderated reactors, based on Canada's CANDU reactor design. Because these reactors use natural uranium as fuel, like plutonium production

meantime, most states will likely choose the reactors currently being marketed, which range predominantly from 1,000 to 1,600 MWe.

Distribution of a Major Expansion

The 2003 MIT study used an economic model to assess the distribution of expanded nuclear energy capacity. MIT assumed that states would seek to achieve certain rates of per capita electricity consumption goals (4,000 kWh). Although this is not a distribution designed to achieve optimal CO_2 reductions, it is expansion at a level significant enough (1,500 GWe) to have an effect on CO_2 emissions. Figure 9 is based primarily on the MIT projections, with some variations according to countries' stated intentions.[102] Figure 9 compares three scenarios: the first (blue rings) shows modest growth as forecasted by the Energy Information Administration; the second shows states' plans (red rings); and the third shows expansion to 1,500 GWe (green rings).

Such a fourfold expansion of nuclear energy would entail significant new production requirements for uranium enrichment—as shown in figure 10—and possibly, reprocessing. The MIT study anticipated that fifty-four states would have reactor capacities that could possibly justify indigenous uranium enrichment. If a capability of 10 GWe is considered the threshold at which indigenous enrichment becomes cost-effective, more than fifteen additional states could find it advantageous to engage in uranium enrichment.

The Distribution of Nuclear Energy and Supply Constraints

Major expansion could be hindered by potential supply constraints as described above, but also by the specific challenges of nuclear energy. If so, how could this affect the distribution of nuclear energy's growth?

reactors, they produce weapons-quality plutonium. In addition, they do not need to be shut down to be refueled, which makes monitoring for diversion of fuel more difficult. As a result, many experts believe they pose a greater proliferation risk than light-water reactors.

102. There are slight differences between the scenario depicted here and the MIT assessment. For example, a few countries that the MIT high 2050 case included but are not included here are countries that currently have laws restricting nuclear energy, for example, Austria. Other countries that the MIT study ruled out but are included here because they have stated an intention to develop nuclear energy are those in the Middle East and Africa (Jordan, United Arab Emirates, Saudi Arabia, Kuwait, Yemen, and Tunisia), and less-developed countries such as Bangladesh, Nigeria, Ghana, and Yemen.

FIGURE 9

An Illustrative Expansion of Nuclear Energy Capacity to 1,500 Gigawatts Electric to Reduce Carbon Emissions

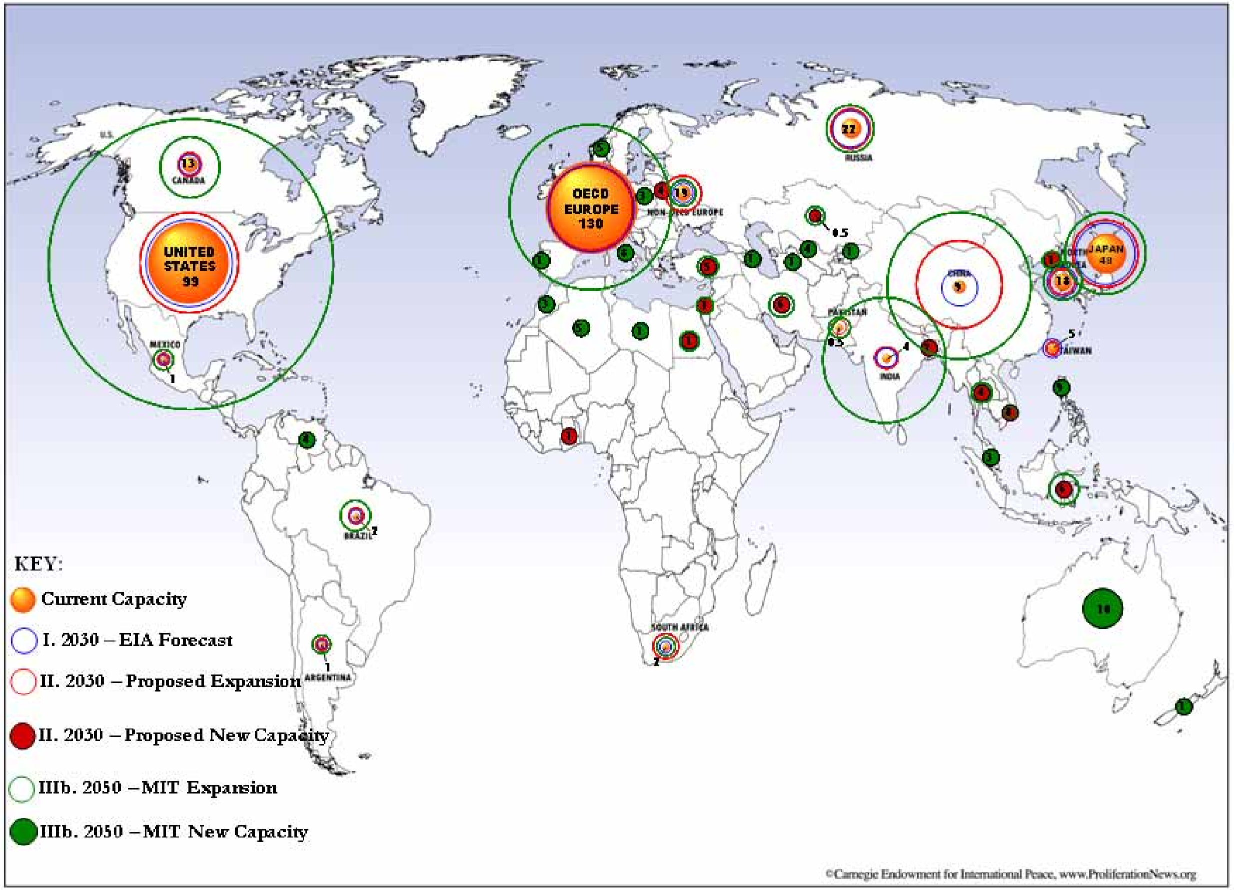
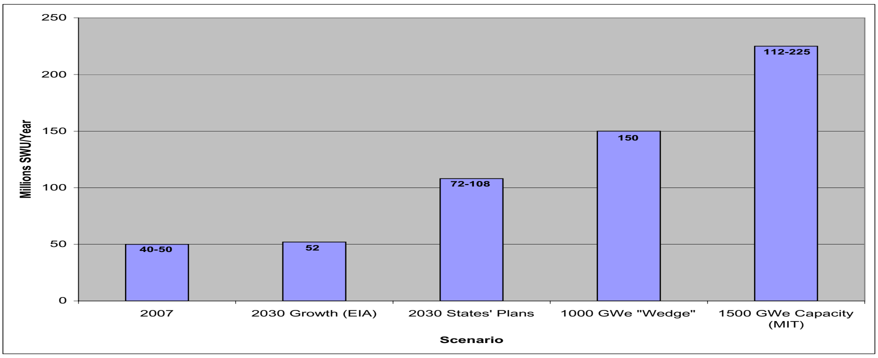


FIGURE 10
Enrichment Implications of Reactor Capacity Growth



SWU = separative work unit, a measure of capacity in uranium enrichment. The EIA 2030 growth scenario corresponds to scenario 1 in Figure 9; the 2030 states' plans corresponds to scenario 2 in Figure 9 and the 1500 GWe capacity corresponds to scenario 3 in Figure 9.

If the demand for power reactors exceeds the nuclear industry's capability to supply them, several possible outcomes could emerge. Vendors could focus on their bottom line, seeking contracts in countries that can subsidize nuclear energy. This would include states with more government involvement in industry and, probably, oil-rich states. Poorer countries, even if they had high electricity demand, would not be a high priority. Another possibility is that vendors would focus on surer bets and sell reactors to countries that already have operating nuclear power plants. A third possibility is that Russia, along with Kazakhstan, could supply reactors to states that are less attractive to Western vendors.

Alternatively, a second tier of suppliers—such as China, India, and Kazakhstan—could develop to meet increased demand for reactors. South Korea could seek a larger supplier role and market indigenously designed reactors. A short-term implication could be reduced quality in components.[103] A longer-term implication could be the export of more pressurized heavy-water reactors by India and possibly others. To many developing countries, such reactors could be attractive because they are smaller and use natural uranium for fuel, which avoids the need for enrichment services. However, such reactors pose proliferation risks because they are more difficult to monitor regarding the diversion of fuel rods, from which plutonium for weapons could be extracted.

103. "Utilities Fret As Reactor-Parts Suppliers Shrink," *Wall Street Journal*, April 11, 2008.

PROLIFERATION RISKS

In 2008, the International Security Advisory Board of the State Department concluded that "the rise in nuclear power worldwide, and particularly within Third World countries, inevitably increases the risks of proliferation." The risks differ according to whether expansion is limited or significant.

Risks of Limited Expansion

New nuclear capabilities, particularly in some geographic locations, could increase the probability of proliferation and could pose security risks because of political instability or the existence of terrorist groups. For those countries that do not already have nuclear research reactors, developing the scientific, engineering, and technical base associated with nuclear power would enhance their proliferation potential. Regional dynamics could also play a role in increasing risks. The neighboring countries of Egypt, Jordan, Indonesia, Malaysia, Morocco, Nigeria, Vietnam, and the Gulf Cooperation Council countries might worry about and respond to the possibility that these countries will develop weapons programs. Political instability raises additional concerns. For example, the Group of Eight states are reportedly concerned about Nigeria's plans to develop nuclear power, not because they have fears about Nigeria's nuclear weapons intentions but because of Nigeria's history of political instability.[104] The possibility of nuclear reactors in Yemen would raise similar concerns.

If nuclear expansion is limited by infrastructure constraints, a different kind of risk could emerge. Advanced nuclear states have largely generated the global surge of enthusiasm for nuclear energy. Expectations are high that nuclear technology will be shared and that reactor sales will be facilitated. However, any number of developments could complicate the deployment of power reactors in developing states. For example, some states may diligently implement all the recommendations for safety, physical protection, and regulatory infrastructure, but they could lag in developing safety and security cultures, which are necessary for the reliable and safe operation of nuclear power plants. Moreover, developing states may find that the large reactors for sale are incompatible with their transmission grids, or they may choose to buy

104. "G-8 Concerns over Nigeria Nuclear Programme," *Journal of Turkish Weekly*, July 1, 2008. See also "Nigeria: FG to Generate 5000 MW Electricity from Nuclear Energy," *This Day*, July 30, 2008.

just one reactor, which is costly for them and less attractive to vendors. The natural caution of vendors in this situation, if it is widespread, could be misinterpreted as discrimination.

Even if reactors are sold widely to developing states, attempts to limit access to other parts of the fuel cycle—enrichment and reprocessing—could heighten frustrations. This could result in reluctance to provide the IAEA with the resources it needs, slower implementation of the safeguards-strengthening measures in the 1997 Model Additional Protocol, and difficulty in reaching agreement on additional measures to strengthen the nonproliferation regime.

The discussion since 2004 within the Nuclear Suppliers Group (NSG) about new criteria to restrict enrichment and reprocessing transfers illustrates the pitfalls of an approach that promotes nuclear energy for all but only limited nuclear fuel cycles for most. President Bush suggested in February 2004 in a speech at the National Defense University that nuclear suppliers prohibit the transfer of sensitive nuclear technology to states that did not already have those technologies. Since then, the NSG has discussed how to implement that prohibition. So far, several states have been unwilling to be relegated to the "have-not" category, including Canada, one of the largest suppliers of uranium ore. In fact, Canada may move quickly to establish an enrichment capability before the door closes. South Africa may resurrect the enrichment technique it developed for its weapons program or seek centrifuge enrichment technology. Ukraine sought cooperation with foreign partners "to obtain the full cycle of enrichment and production of nuclear fuel" to counter uncertain gas supplies from Russia, but Ukraine had agreed by the end of 2008 to join the Angarsk enrichment joint venture. Although NSG members already followed a policy of restraint on such transfers, the promise of major nuclear expansion appears to be eroding agreement in this area. Additional enrichment capacity in some of these states may not cause alarm, but if they are successful, it may become more difficult to justify why other states should not develop such capabilities.

In light of these difficulties, advanced states have been encouraging other states to voluntarily forswear enrichment and reprocessing as a confidence-building measure. In 2008, the United Arab Emirates released its Policy of the United Arab Emirates on the Evaluation and Potential Development of Peaceful Nuclear Energy. Not coincidentally, the Emirates' foreign minister and U.S. secretary of state Condoleezza Rice signed a memorandum of understanding on peaceful nuclear cooperation the next day (followed by a cooperation agreement several months later). The Emirates renounced any intention to develop a domestic enrichment and reprocessing capability and reportedly will pass legislation that would criminalize such activities within the country. The policy document cites economic infeasibility of such activities for a small nuclear fleet, international concerns about sensitive fuel cycle capabilities in developing countries, and the dual-use nature of components employed in fuel fabrication and processing. Instead, the Emirates will seek long-term arrangements with governments and contractors.

It is too soon to tell whether a significant number of states will follow in the United Arab Emirates' footsteps. It is also unclear what consequences would ensue should the Emirates' voluntary decisions be reversed. One suggestion by the State Department's International Advisory Board was to reach agreement among suppliers that supply would be cut off if such voluntary decisions were reversed, and that consequences would be clearly spelled out in commercial contracts. This could be particularly difficult to implement. At the very least, such an approach depends on the success of extensive diplomatic negotiations.

Risks of Major Expansion

An expansion of nuclear power large enough to make a significant contribution to climate change mitigation—doubling, tripling, or quadrupling power reactor capacity—would present some of the risks described above, as well as new ones.

As long as light-water reactors remain the technology of choice, doubling or tripling the number of reactors will require more uranium enrichment plants. If all projected plans for power reactors by 2030 are realized, twice as much enriched uranium would need to be produced. Expansion according to climate change scenarios would require three to four times as much uranium enrichment capacity compared with today. If enrichment capabilities in the eleven countries that already enrich uranium were simply expanded, the risk of proliferation would not necessarily grow. But that is an unlikely scenario, given the lack of agreement among suppliers and recipients described above. Countries with significant uranium resources might choose to enrich for export (although the economics of this are not clear), and/or countries with more than ten reactors might find it economically feasible to enrich uranium for their own use. Under a 1,500-GWe capacity scenario, there could be fifteen additional countries that could have an economic justification for enriching their own uranium (with 10 GWe or more of nuclear capacity).

Nuclear power expansion will likewise increase the amount of nuclear waste generated. A large, 1-GWe power plant produces an average of 20 metric tons of spent fuel per year. Adding one "nuclear wedge" of 700 GWe will generate 273,000 cumulative tons of spent fuel by 2050, according to the Natural Resources Defense Council. The 2003 MIT study estimated that adding 1,000 GWe of reactor capacity globally would require opening a new repository on the scale of Yucca Mountain (70,000-ton capacity) every three and a half years.[105] It is unlikely that states just starting to deploy nuclear reactors would seek to reprocess their irradiated fuel, but until supplier states agree to either take back spent fuel for storage or for reprocessing, the reprocessing option would remain open for these new nuclear states. Regardless of whether these new states reprocess or whether supplier states reprocess, a nuclear expansion that embraces reprocessing as necessary to reduce spent-fuel accumulation could result in more plutonium in transit, providing more potential targets for diversion or attack. An expansion that includes widespread installation of fast reactors would similarly increase targets for diversion or attack.

Major expansion would also significantly strain the resources and capabilities of the IAEA's safeguards system. More nuclear facilities will require additional safeguards effort by IAEA inspectors. Although reactors themselves require relatively few inspection days, a nuclear expansion that yields more states with bulk-handling facilities (enrichment and reprocessing) could overwhelm the system. Some of this strain is avoided now because major enrichment and reprocessing facilities are located in nuclear weapon states, which are not required to have inspections. Moreover, the largest enrichment and reprocessing plants under safeguards now are under EURATOM safeguards; the IAEA's role in verifying material balances in those plants is limited by the IAEA-EURATOM agreement. The only experience in safeguarding commercial-scale enrichment and reprocessing plants outside EURATOM in a non-nuclear-weapon state is in Japan. In addition, critics of the IAEA suggest that current methods of inspection at bulk-

105. Note that the 70,000-ton capacity of Yucca is a legislated limit, and other estimates have suggested that Yucca could hold three to ten times that limit. Also, there is no reason why a geologic repository could not be larger than the size of Yucca, so this measure is a bit misleading.

handling facilities cannot provide timely warning of diversion of a significant quantity of special nuclear material. In particular, safeguards approaches at enrichment plants do not adequately address the potential for undeclared inputs into such plants. Additional non–nuclear-weapon states with such facilities would require additional scrutiny.

POLICY PRIORITIES

The United States has played a leading role for decades in helping reduce nuclear proliferation risks and promoting the peaceful uses of nuclear energy. Thirty years ago, the U.S. government abandoned commercial spent-fuel reprocessing because of the proliferation risks posed by separated plutonium in the civilian fuel cycle. At that time, and for many subsequent years, critics argued that U.S. influence over other countries' fuel cycle decisions would decline as its nuclear energy capabilities waned. Under the Bush administration, U.S. nuclear energy policy sought to close the fuel cycle using reprocessing technologies described as proliferation-resistant because they would not separate out plutonium. At the same time, the United States sought to persuade other countries not to engage in sensitive fuel cycle operations like enrichment or reprocessing while promoting nuclear power abroad for its climate change virtues. The promotion of nuclear energy abroad has succeeded in generating enthusiasm for nuclear energy where there was relatively little before, but unfortunately it has also generated enthusiasm for enrichment and reprocessing that perhaps had been repressed previously.

Promoting Nuclear Energy at Home

From the beginning of his administration, President Bush vigorously promoted nuclear energy at home. In 2001, the National Energy Policy Development Group, chaired by Vice President Dick Cheney, recommended that Bush "support the expansion of nuclear energy in the United States as a major component of our national energy policy." Specifically, the group recommended that the United States "reexamine its policies to allow for research, development and deployment of fuel conditioning methods . . . that reduce waste streams and enhance proliferation resistance. In doing so, the United States will continue to discourage the accumulation of separated plutonium worldwide." The group also recommended that the United States consider technologies in collaboration with international partners "to develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant."

The Bush administration advocated nuclear energy both for its contributions to energy security and its ability to generate carbon-free electricity. For example, the February 2006 Advanced Energy Initiative advocated safe, clean nuclear energy to help reduce dependence on foreign sources of energy.[106] The report highlighted nuclear power's "domestic" characteristics and its ability to provide energy security, stating that "North American uranium reserves are more than sufficient for the foreseeable future." Although nuclear energy was touted by President Bush as clean and safe before climate change was openly addressed as a policy issue, recent statements have extolled nuclear energy's climate change virtues. In a speech on April 16, 2008, President Bush described the right and wrong ways to approach climate change legislation:

> The wrong way is to jeopardize our energy and economic security by abandoning nuclear power and our nation's huge reserves of coal. The right way is to promote more emission-free nuclear power.

Promoting nuclear energy at home has included real money. For example, DOE's research and development budget for nuclear energy tripled from 2001 to 2009.[107] At the same time, DOE's research and development (R&D) budget for renewables about doubled, and R&D for fossil fuels declined.[108] DOE initiated a joint government/industry program in 2002 called Nuclear Power 2010 to develop advanced reactor technologies and demonstrate new regulatory processes. Significant subsidies have also been a part of the effort to help jump-start the U.S. nuclear industry. In 2005, Congress passed the Energy Policy Act, which provided a combination of several incentives, including production

106. U.S. National Economic Policy Council, *Advanced Energy Initiative*, February 2006, www.whitehouse.gov/stateoftheunion/2006/energy/energy_booklet.pdf.

107. See data contained in K. S. Gallagher, "DOE Budget Authority for Energy Research, Development, and Demonstration Database," Energy Technology Innovation Policy, John F. Kennedy School of Government, Harvard University, February 2008, http://belfercenter.ksg.harvard.edu/publication/18152doe_budget_authority_for_energy_research_development_and_ demonstration_database.htm.

108. See Mark E. Gaffigan, U.S. Government Accountability Office, "Advanced Energy Technologies: Budget Trends and Challenges for DoE's Energy R&D Program," Testimony before the Subcommittee on Energy and Environment, Committee on Science and Technology, U.S. House of Representatives, March 5, 2008, GAO-08-556T, 6.

tax credits, energy facility loan guarantees, and standby support contracts. Since then, ten applications for combined construction and operating licenses for nuclear power plants have been filed, and nine more reportedly are being prepared. Such applications for licenses do not necessarily imply that the power plants will be built. Loan guarantees, in particular, have been cited by industry sources as so critical that new construction may not happen without them. From an initial $4 billion authorized in fiscal 2007, the number has jumped to $18.5 billion approved in the fiscal 2008 budget (not including $2 billion for uranium enrichment). DOE expects to issue its first loan guarantee in 2009.[109]

Many observers claim that the rejuvenating of U.S. nuclear energy is critical to reclaiming U.S. global nuclear leadership. Beyond new reactor construction, R&D, and infrastructure development, plans to promote nuclear energy in the United States now include the development of fast reactors to burn plutonium and the "recycling" of waste for that purpose. One objective of these programs is to find a solution to the buildup of tons of spent fuel in the United States that is awaiting geologic storage at Yucca Mountain. Supporters of reprocessing assume that a second repository will be impossible to open, given the delays experienced already for the site at Yucca Mountain. The basic idea is to reduce the volume of nuclear waste by reusing the fuel in fast reactors, which can burn up more of the material.[110]

These plans essentially have overturned a thirty-year policy of discouraging the use of plutonium in the U.S. civilian nuclear fuel cycle for proliferation reasons.[111] Whether the U.S. nuclear industry will wholeheartedly embrace spent-fuel reprocessing and the development of advanced burner reactors that will require billions of dollars of in-

109. U.S. Department of Energy, "Nuclear Power Deployment Scorecard," July 2, 2008, www.ne.doe.gov/np2010/neScorecard/neScorecard_financial.html.

110. Power reactors in the United States are mostly thermal power reactors. These reactors use low-enriched uranium as fuel and water to slow down, or moderate, the speed of neutrons to a "thermal level" so that more fissioning can occur. In so-called fast reactors, different kinds of fuel are used with no attempt to slow down the speed of neutrons. Fast reactors operate at higher temperatures and have a wider spectrum across which fissioning can occur, allowing a broader menu of actinides to be fissioned and therefore "burned up." The resulting actinides are shorter-lived radionuclides, which are much more radioactive but decay much more quickly.

111. The Reagan administration, which funded reprocessing R&D and the licensing of the privately owned Barnwell reprocessing facility, did not provide government funding for Barnwell, which ultimately was not economically viable.

vestment is unclear.[112] Thus far, the U.S. Congress has taken a “go slow” approach, delaying demonstration of advanced recycling technologies until more research can proceed.[113] A key report by the National Academy of Sciences in 2007 recommended the same.

For thirty years, the United States has promoted the idea that nuclear power does not require reprocessing. Now, however, a more muddled message is being broadcast—that a closed nuclear fuel cycle is the purview of advanced nuclear states. Apparently, the proliferation resistance of the future recycling technology is good enough to be deployed in advanced nuclear states, but not in not-so-advanced states. In this context, it is difficult to see how a technical fix—proliferation-resistant recycling—will overcome the desires of some states to follow in the United States’ footsteps. What is needed is widespread agreement on institutional barriers to developing sensitive technologies that can be used for peaceful nuclear energy or for nuclear weapons.

Promoting Nuclear Energy Abroad

In addition to promoting nuclear energy at home, U.S. officials have promoted nuclear energy abroad through diplomacy, multilateral initiatives, and individual nuclear cooperation agreements. These efforts are undoubtedly motivated by a need to help ensure that nuclear energy is used only for peaceful purposes, but there is also ample evidence of other motivations, such as enhancing economic, trade, and bilateral relations.

Probably the best-known program to promote nuclear energy is the Global Nuclear Energy Partnership (GNEP), unveiled in February 2006. In many ways, GNEP struggles under the weight of its own contradictions. Program responsibilities are split between nuclear energy promoters in DOE’s Office of Nuclear Energy and nuclear nonproliferation staff in DOE’s National Nuclear Security Administration. GNEP supports a two-tiered approach to partnership: cooperation with ad-

112. Matthew Bunn, “Assessing the Benefits, Costs, and Risks of Near-Term Reprocessing and Alternatives,” Testimony before the Subcommittee on Energy and Water Appropriations, Senate Appropriations Committee, September 14, 2006.

113. See Senate Hearing 110-306, “Global Nuclear Energy Partnership,” Hearing Before the Committee on Energy and Natural Resources, U.S. Senate, 110th Congress, First Session, to Receive Testimony on the Global Nuclear Energy Partnership as It Relates to U.S. Policy on Nuclear Fuel Management, November 14, 2007.

vanced states, which includes the development of fast reactor designs and proliferation-resistant fuel "recycling"; and cooperation with less-advanced states in developing small, proliferation-resistant reactors and fuel assurances. GNEP helps U.S. domestic efforts to develop fast reactors and spent-fuel recycling by fostering collaboration between U.S. officials and scientists and French, Japanese, Russian, and other states' officials and scientists. Another set of collaborative efforts would develop small, cost-effective proliferation-resistant reactors for developing countries. The assumption is that small reactors, coupled with reliable fuel supply assurances and a framework for handling spent fuel, should be incentive enough for states to forgo uranium enrichment and reprocessing activities. However, GNEP collaborators so far are focusing on enhancing nuclear infrastructure and reliable fuel assurances.[114]

GNEP's principles and goals have evolved since 2006. There is no longer any mention in its principles of countries agreeing to refrain from fuel cycle activities, although there is mention of "international supply frameworks." There is also no obligation for other countries that currently reprocess spent fuel to modify their facilities to use a more proliferation-resistant technology. In the end, GNEP could simply prompt more states to enrich and reprocess.

If pursued to its fullest, GNEP would not be completely realized for decades. Many of the reactor technologies will not be ready before 2030. Ernest Moniz, former DOE undersecretary and coauthor of the 2003 MIT study, noted that "it makes sense to store spent fuel for on the order of a century prior to doing whatever is planned. This conveniently provides several decades to find out if advanced fuel cycles will materialize."[115]

In addition to cooperation through GNEP, the United States has been promoting what is known as the "Attractive Offer," bilateral initiatives with Russia to promote nuclear energy, and individual nuclear cooperation agreements.[116] The "Attractive Offer" was developed by the United States and six other supplier countries in 2006 to enhance

114. GNEP Steering Group Action Plan, December 13, 2007, www.gneppartnership.org/docs/GNEP_actionplan.pdf.

115. Ernest Moniz, "Toward an Integrated Fuel Cycle," *EPRI Journal*, Spring 2008, 29.

116. The offer is officially called "Six Country Concept for Reliable Access to Nuclear Fuel," which was communicated to the Board of Governors of the International Atomic Energy Agency by France, Germany, the Netherlands, Russia, the United Kingdom, and the United States on May 31, 2006.

the reliability of fuel supplies and provide incentives for states to abjure developing sensitive nuclear technologies. It would add a layer of assurance for both recipients and suppliers; the IAEA would help facilitate the acquisition of reactors, fuel supplies, and services, but it would also assess the nonproliferation credentials of recipient states. Key requirements would include adoption of the Additional Protocol, which contains measures to strengthen the application of IAEA safeguards, and written commitments by recipient states not to use or export sensitive nuclear technologies. Little progress has been made so far in implementing the Attractive Offer, and according to U.S. officials, many elements of the U.S.–Russian initiatives have slowed as a natural outcome of frostier relations. It is uncertain whether the Obama administration will pursue efforts similar to the 2007 Bush–Putin declaration on nuclear energy and nonproliferation, the purpose of which was to facilitate supply of modern, safe, and more proliferation-resistant power and research reactors; promote programs to develop requirements for nuclear reactors for developing countries; facilitate and support financing to aid construction; and provide assistance to develop the necessary infrastructure in new nuclear states.[117]

The United States has also promoted nuclear cooperation agreements with other countries. Though these are framework arrangements that do not actually entail exports of nuclear equipment, materials, or technology, they are important because they are generally viewed as a symbol of a close relationship with the United States. One particularly sharp example is the United States–India peaceful nuclear cooperation agreement, approved by Congress in October 2008. A troubling aspect of this agreement is not just that the United States lifted its restriction on cooperation with a state that has not signed the Non-Proliferation Treaty, but also that U.S. policies on restricting cooperation in sensitive nuclear technologies were lifted for India. This fact has not been lost on other countries, which are likely to press the United States for similar concessions. Another troubling outcome of that agreement is the potential for other states to supply sensitive technology to India. India is likely to make the argument to other NSG suppliers that if the United States could agree in principle to cooperate on enrichment and reprocessing, so can they.

In 2008, a nuclear cooperation agreement with Turkey entered into force, and another with Russia was submitted to the U.S. Con-

117. See "Joint Declaration on Nuclear Energy and Nonproliferation," July 3, 2007, www.whitehouse.gov/news/releases/2007/07/20070703.html.

gress. The Russian agreement was controversial in Congress because of Russia's engagement with Iran in sensitive trade areas, including nuclear technology (the Bushehr reactor), missiles, and advanced conventional weapons. Before the agreement was withdrawn from congressional consideration because of Russian support for Abkhazia and Ossetia, supporters maintained that that agreement would be crucial for future cooperation with Russia under GNEP. Russian willingness to either store or reprocess U.S.-origin fuel that has been irradiated in power reactors around the globe would be a huge step forward for GNEP, but a nuclear cooperation agreement with the United States is necessary for such transfers. Also in late 2008, the United States initialed a nuclear cooperation agreement with the United Arab Emirates and a memorandum of understanding with Saudi Arabia on nuclear cooperation.

The United States is not alone in its nuclear diplomacy. In fact, all the major suppliers have made significant efforts to court potential nuclear clients. France is perhaps the most aggressive, but Russia, Japan, and the United Kingdom have all been involved, particularly in the Middle East. For example, the United Arab Emirates reportedly has signed cooperation agreements with France, the United Kingdom, and South Korea, and is seeking agreements with Japan and Russia. It is not surprising that a record number of countries have expressed interest in developing nuclear power.

STEPS TO MITIGATE THE RISKS OF NUCLEAR PROLIFERATION

Nuclear nonproliferation tends to garner attention when crises erupt—for example, when a country like North Korea tests a nuclear weapon or Iranian officials refuse to allow international inspectors access to suspect sites. In large measure, however, the real work of nuclear nonproliferation is in crafting rules that provide broad assurances of the peaceful uses of nuclear energy. Such rules are best adopted in anticipation of general trends, rather than in reaction to a crisis.

As this report explains, it is not clear that a major expansion of nuclear energy is feasible or desirable in the next twenty years. Nonetheless, some countries that do not now have nuclear power may pursue building power plants because of the nuclear enthusiasm generated by the major suppliers, because of the prestige associated with nuclear power, and, possibly, to hedge their bets in politically volatile regions.

It is imperative that states act now to mitigate the proliferation risks that nuclear expansion could pose by implementing the following seven steps.

Step 1: Compare All Energy Options, Including Efficiency

Carbon-free electricity will require enormous investments, and it will be important to weigh carefully the costs and benefits of all solutions, particularly efficiency. Just as all options for producing ethanol should have been compared before subsidizing corn-based ethanol in the United States, so too should the costs and benefits of nuclear energy be weighed carefully before subsidizing it over other electricity solutions.

The urgency of climate change requires deploying the cheapest and fastest of the low-carbon energy options first. Yet countries need to assess the entire spectrum of reducing carbon emissions, not just reductions in the electricity sector. Recently, there have been calls to establish a global energy agency.[118] At a minimum, the IAEA and the IEA should collaborate to identify alternatives to nuclear power for states seeking their guidance. Under a climate change imperative, existing agencies or a new commission could work with states to identify the entire range of energy options to enhance energy security and reduce carbon emissions, particularly enhancing efficiency.[119]

Step 2: Take the Glamour Out of Nuclear Cooperation

Nuclear energy is often regarded by countries as a symbol of great prowess, rather than simply as a way to produce electricity. Because states have an inalienable right to pursue nuclear energy for peaceful purposes, part of the challenge in leveling the energy playing field will be addressing the allure of nuclear power. Some of the current proposals to provide nuclear power to developing countries entail little technology transfer. Some countries are considering contracting out virtually all the responsibilities of running nuclear power plants, including staffing. Russia has a proposal for floating reactors that envisions dock-

118. Mohamed ElBaradei, "A Global Agency is Needed for the Energy Crisis," *Financial Times*, July 24, 2008.

119. There are many different paths to reducing carbon emissions. This report has cited several proposed by the International Energy Agency. See also Arjun Makhijani, *Carbon-Free and Nuclear-Free* (Takoma Park, Md.: RDR Books and IEER Press, 2007).

ing the reactors offshore and then removing them when their service lives are complete. It is possible that the less a recipient state is required to do (building, staffing, operating, refueling, maintaining), the less prestigious nuclear power will be. It is not clear, however, how nuclear liability issues would be handled in that case.

In part, the glamour of nuclear power is enhanced by the perceived prestige of nuclear cooperation agreements. The 2008 United States–India nuclear cooperation agreement illustrates the importance some states attach to nuclear cooperation, even though the framework agreements in reality do not guarantee trade. Yet these agreements are often seen as a symbol of close and strategic relationships between states. Nicolas Sarkozy's high-profile trips to the Middle East to promote nuclear energy likewise have contributed to the glamour factor.

Although some might argue that cooperation agreements are a way to provide the prestige that some states seek, this approach is not sustainable over the long term if that recipient sees little technical cooperation. Another approach would be to conduct discussions strictly on a government-to-government level, subsuming nuclear cooperation under a broader rubric of energy cooperation, rather than as a separate diplomatic venue. This would be easier in a framework where all energy options are considered, as suggested above.

Step 3: Adopt the Additional Protocol as a Requirement

The IAEA's Model Additional Protocol, which contains measures to strengthen the IAEA's international safeguards system, was approved in 1997, yet its adoption has not been mandatory. One hundred states do not yet have a protocol in force. The measures—which include increased access for inspectors, a wider array of information about a state's entire fuel cycle, provisions for short-notice inspections, and new monitoring techniques—are essential to enhance the IAEA's ability to detect undeclared nuclear activities in a state. The additional protocol needs to become the new benchmark for nuclear supply within the NSG. Although this has been under discussion for several years, a few countries within the NSG have not yet signed or ratified such protocols, including Argentina and Brazil, and therefore are hesitant to make this a condition of supply. All countries should incorporate a requirement for an Additional Protocol into their nuclear cooperation agreements as well as in vendor contracts.

Step 4: Supply Nuclear Reactors and Their Components Responsibly

The nuclear industry understands its own interdependence, particularly in the area of nuclear safety. The common refrain of "a nuclear accident anywhere affects everyone everywhere" can be extended to nuclear security and to proliferation. Yet in an expanded nuclear world, there could be tremendous commercial pressure to supply nuclear reactors and components to states that may not yet have all of their regulatory, safety, and security infrastructure in place. To mitigate risk in such situations, vendors need to agree on minimum requirements for the sale of nuclear reactors and components and make these standard clauses in contracts. It will be important to reach beyond the NSG to other potential suppliers, particularly India and Pakistan. Some of the minimum requirements might include signing the existing safety, security, and nuclear waste conventions mentioned earlier in this report.

Step 5: Increase Transparency and Tighten Restrictions on Sensitive Technologies

More transparency is needed with regard to peaceful nuclear cooperation agreements. Although U.S. agreements are a matter of public record because of the requirement for congressional approval, this is not always the case in other countries. Sharing the text of cooperation agreements could help promote the standardization of nonproliferation requirements, including restrictions on sensitive technologies.

The Nuclear Suppliers Group needs to make progress on tightening restrictions on sensitive technologies. The United States and other NSG members missed an opportunity to ban the sale of these technologies to India when the NSG approved an exemption in 2008 for India from its rules. One outcome of negotiations with Congress over the United States–India deal was a promise by Secretary of State Rice to pursue further restrictions at the NSG's November 2008 meeting. As of this writing, a decision was referred to capitals and if not resolved soon, it should be a top priority for the Obama administration.

Step 6: Give Priority to Small and Proliferation-Resistant Reactor Designs

Proliferation resistance, as defined by the IAEA, is a "characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technologies by states in order to acquire nuclear weapons or other nuclear explosive devices."[120]

Four approaches can enhance proliferation resistance: technical design, how facilities are operated, institutional arrangements, and safeguards. The Global Nuclear Energy Partnership seems to have focused its efforts so far on institutional arrangements, but it could devote more effort to help commercialize not just grid-appropriate (that is, smaller) reactors, but also those with more proliferation-resistant reactor designs that incorporate passive safety features. GNEP should build on the work of the Generation IV Forum in this regard. Some of the smaller reactors under consideration—such as the Russian floating reactors or the Pebble Bed Modular Reactor—should be carefully vetted against international standards with respect to safety, safeguardability, and security.

Step 7: Phase Out National Enrichment Capabilities Under a Fissile Material Production Cutoff Treaty

One of the most difficult aspects of restricting access to sensitive nuclear technologies like enrichment and reprocessing is the element of national prestige that is often attached to these high-profile projects. Many non–nuclear-weapon states have rejected the notion that they should forgo sensitive nuclear technologies, as President Bush has urged since 2004, because they reject the creation of yet another discriminatory approach under the Non-Proliferation Treaty. The Bush proposal would create one category for states with full fuel cycles and one for states with limited fuel cycles.

One way of divorcing this element of national pride from the technology is ultimately to "denationalize" those activities, or get beyond a tiered system by requiring that future facilities be multinationally owned and operated. Over time, existing plants would need to be converted to multinational ownership, operation, and regulation as well. Such an approach is likely to face considerable resistance, but it could be broached within the context of a fissile material production cutoff treaty. Such a treaty could ban not just the production of fissile material for weapons but also all national enrichment capabilities. For example, the treaty could require all new fissile material production capabilities immediately after entry into force to have multinational ownership, and

120. International Atomic Energy Agency, "Proliferation Resistance Fundamentals of Future Energy Systems," STR-332, December 2002.

it could require existing national sites to be multinationalized five or ten years after its entry into force. In addition to deflecting the element of national prestige, multinational enrichment facilities would raise the probability of detecting clandestine enrichment and hence substantially lower the risk of a national violation of fissile material cutoff treaty restrictions. It is likely that some countries would need, at a minimum, to alter their laws or regulations regarding foreign ownership of these sensitive technologies or plants.

* * *

In 2003, the authors of the MIT study *The Future of Nuclear Power* concluded that "given the difficulties that confront nuclear power, the effort required to overcome them is justified *only* if nuclear power potentially can make a significant impact on the major challenges of global warming, electric supply, and security [emphasis added]"[121] This report has examined nuclear energy's contribution to energy security and the mitigation of climate change, as well as bottlenecks in nuclear supply, and it concludes that a major expansion of nuclear energy may be neither feasible nor desirable to promote.

Renewed interest in nuclear power has been dubbed a "renaissance." Leaving aside the question of whether a renaissance can be forecast in advance rather than recognized and appreciated several hundred years later, the technological advances anticipated for nuclear power are hardly comparable to the artistic, scientific, and cultural advances that occurred during the European Renaissance several centuries ago. There is one grain of truth in the analogy, however: A nuclear renaissance would not go forward without the kind of patronage that made the European renaissance possible. In other words, the widespread deployment of nuclear power around the globe would require massive underwriting. Before embarking on such a path, policy makers need to achieve greater certainty across the range of issues raised in this report. In the meantime, every possible effort should be made to minimize the risks of any potential nuclear expansion. These should include strengthening the rules of nuclear commerce and transparency, deemphasizing the element of national prestige with respect to nuclear energy, undertaking clear-eyed assessments of all available

121. Massachusetts Institute of Technology, *Future of Nuclear Power*.

options for generating electricity options, and limiting the acquisition of sensitive nuclear technologies like uranium enrichment and spent-fuel reprocessing.

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NUCLEAR ENERGY: Rebirth or Resuscitation?

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