Scenarios and Consequences of a Contraction in Global Nuclear Energy Production

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Nuclear electricity production is likely to increase substantially over the next 40 to 50 years, driven by efforts to stabilize greenhouse gas concentrations. Stabilization at a reasonable level (e.g., a doubling of the preindustrial concentration of carbon dioxide in the atmosphere) cannot be achieved without deep reductions in projected carbon dioxide emissions. Coal, which is primarily used to produce electricity, currently accounts for 40 percent of global carbon emissions. Because coal is likely to remain the least-cost method of baseload electricity generation in many regions, its fraction of global electricity supply is projected to increase from 40 to 45 percent by 2030, resulting in a doubling of carbon emissions from coal.[2] Any strategy to reduce global carbon emissions must include policy mechanisms—carbon taxes or cap-and-trade systems—that will raise the price of coal-fired electricity to the point where it would be more expensive in most markets than a low-carbon alternative. Over at least the next 20 years, the lowest-cost source of carbon-free baseload electricity in many markets is likely to be nuclear.

My task, however, is to explore scenarios in which nuclear energy production might decline significantly by 2030. A contraction in nuclear supply might come about in various ways:

- Policies are not widely adopted to reduce carbon emissions. As a result, coal remains substantially cheaper than nuclear in many electricity markets and demand for new reactors does not keep pace with the retirement of existing reactors.

- Other low-carbon alternatives for electricity production prove to be less expensive than new nuclear plants in most markets, or substantial schedule delays and cost overruns destroy investor confidence in nuclear energy, resulting in a decline in demand for new reactors.

- Global electricity demand is much lower than now forecast, possibly as a result of an extended economic recession. Credit shortages make capital-intensive projects, such as nuclear reactors, difficult to finance.

- As a result of safety or security concerns or events, governments and investors lose confidence in nuclear energy and adopt policies that discourage or prohibit the construction of new nuclear reactors, and to shut down existing reactors.

As discussed below, the first four factors are unlikely to produce a decline in global nuclear electricity production. A decline is likely to result only from a marked loss of confidence in nuclear energy as a result of a reactor accident or nuclear terrorism. Even if nuclear energy production declines globally, it is likely to hold its own or even flourish in some countries, due to differences in government policies and electricity markets. But before exploring these factors in more detail, let us review current projections of nuclear electricity generation.

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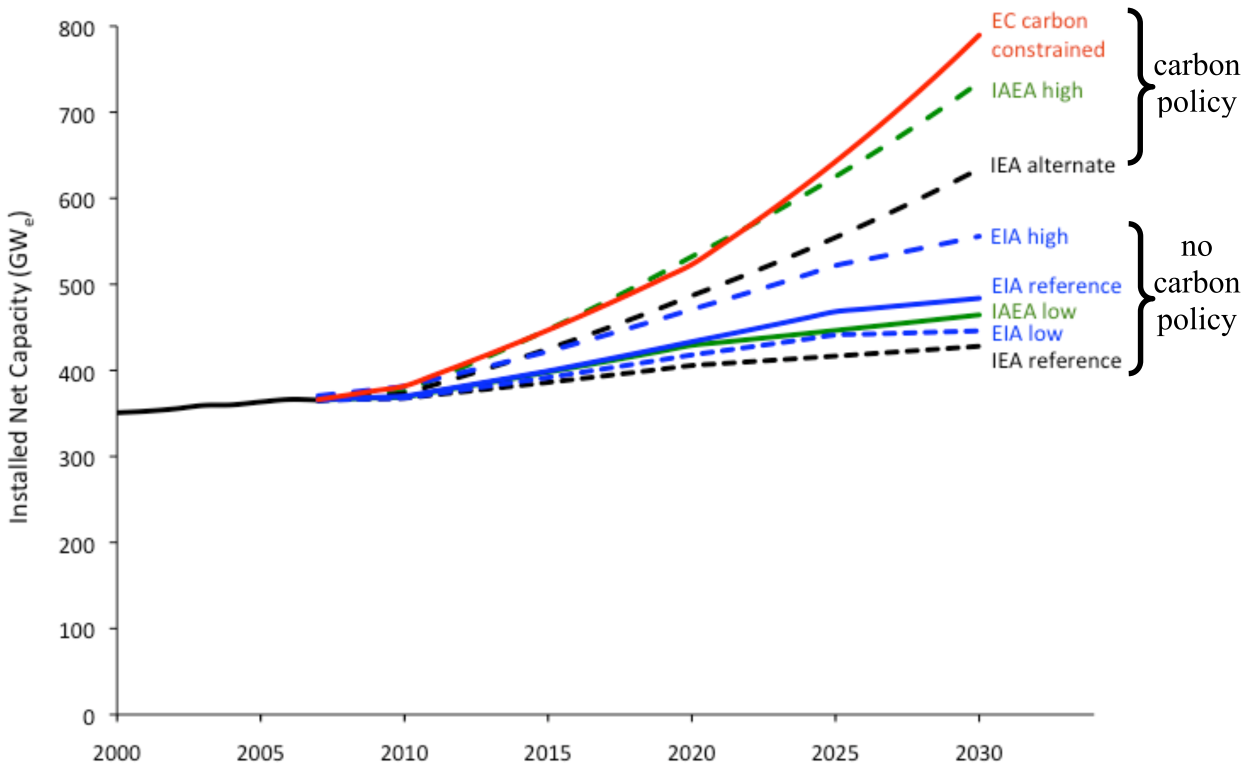
[2] Energy Information Administration, *International Energy Outlook 2008* (Washington, DC: U.S. Department of Energy, DOE/EIA-0484, June 2008).

Reference Scenarios

Figure 1 shows scenarios of world nuclear generating capacity produced recently by the U.S. Energy Information Administration (EIA), the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA), and the European Commission (EC). The EIA scenarios, the IEA reference scenario, and the IAEA low scenario assume no additional policies to reduce carbon emissions; the IEA alternate, IAEA high, and EC carbon-constrained scenarios assume such policies are put in place. In the EIA scenarios, nuclear capacity ranges from a low for low economic growth to a high for high energy prices.

Figure 1. Scenarios for world nuclear capacity (GW_e), 2008-2030.

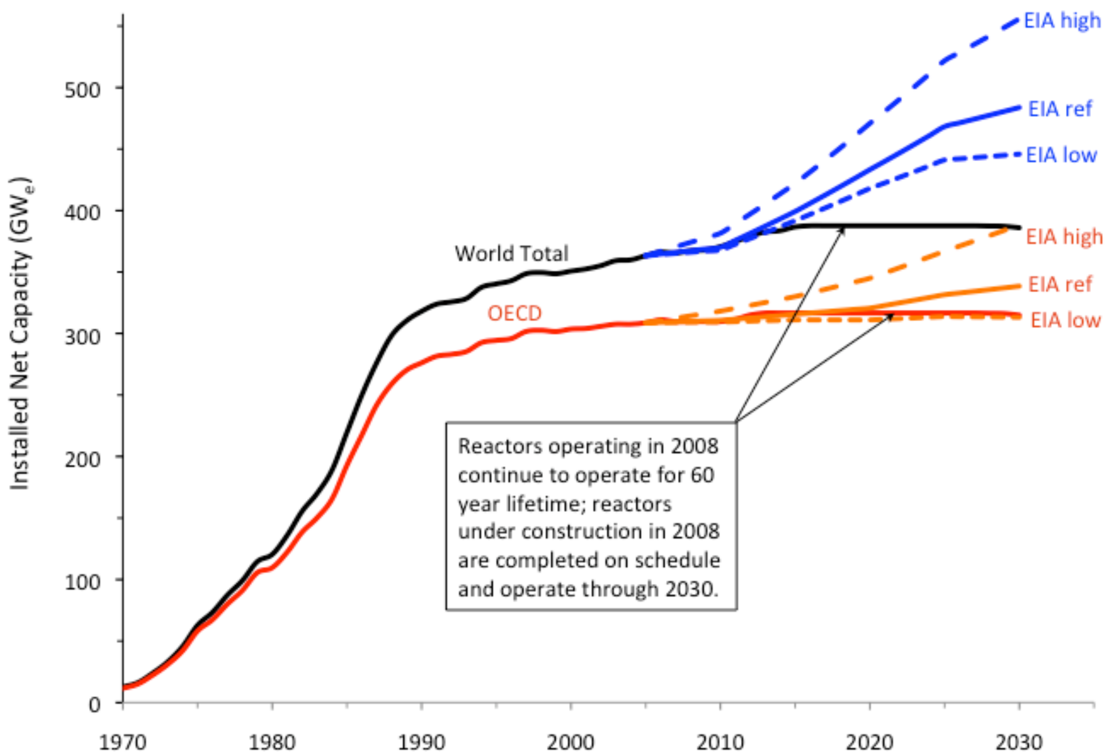


Sources: Energy Information Administration, *International Energy Outlook 2008* (Washington, DC: U.S. Department of Energy, June 2008); International Energy Agency, *World Energy Outlook 2008* (Paris: IEA, 2008); International Atomic Energy Agency, *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030* (Vienna: IAEA, 2008); European Commission, *World Energy Technology Outlook 2050* (Luxembourg: EC, 2006). All projections scaled to match net operating capacity reported by IAEA for 2007.

All of these scenarios indicate growth in nuclear capacity, even without carbon-reduction policies that would make nuclear more competitive with coal and gas, and, in the case of the EIA scenarios, even assuming low economic growth and low fossil-fuel prices. These scenarios also indicate that policies to reduce carbon emissions would cause more rapid growth in nuclear, resulting in a doubling of global capacity by about 2030.

As shown in figure 2, most of the projected growth in nuclear capacity occurs in non-OECD countries. The fraction of global nuclear capacity in the current OECD countries falls from 85 percent in 2007 to 70 percent in 2030 in all EIA scenarios. Also shown in figure 2 is the projected capacity of those reactors that were operating or under construction in 2008, assuming a total operating lifetime of 60 years. Note that the EIA low scenario is nearly identical with the assumption that no new reactors will be built in OECD countries, and that the reactors currently operating will have lifetimes of at least 60 years. If all reactors currently under construction are completed and no additional reactors are built anywhere in the world, nuclear electricity generation would plateau at 13 percent above the 2008 level from 2015 through 2030, assuming that a reactor operating life of 60 years.[3]

Figure 2. EIA scenarios for nuclear capacity in OECD countries and all countries, as well as the projected capacity of reactors operating or under construction in 2008, assuming an operating lifetime of 60 years.



Sources: Energy Information Administration, *International Energy Outlook 2008* (Washington, DC: U.S. Dept. of Energy, June 2008); International Energy Agency, *Nuclear Power Reactors in the World* (Vienna: IAEA, 2008).

It is believed that most light-water reactors can be safely operated for 60 to 80 years. In the United States, nuclear reactors receive an initial operating license for 40 years, but operators can apply for a license renewal for an additional 20 years of operation.[4] As of 2008, about half of

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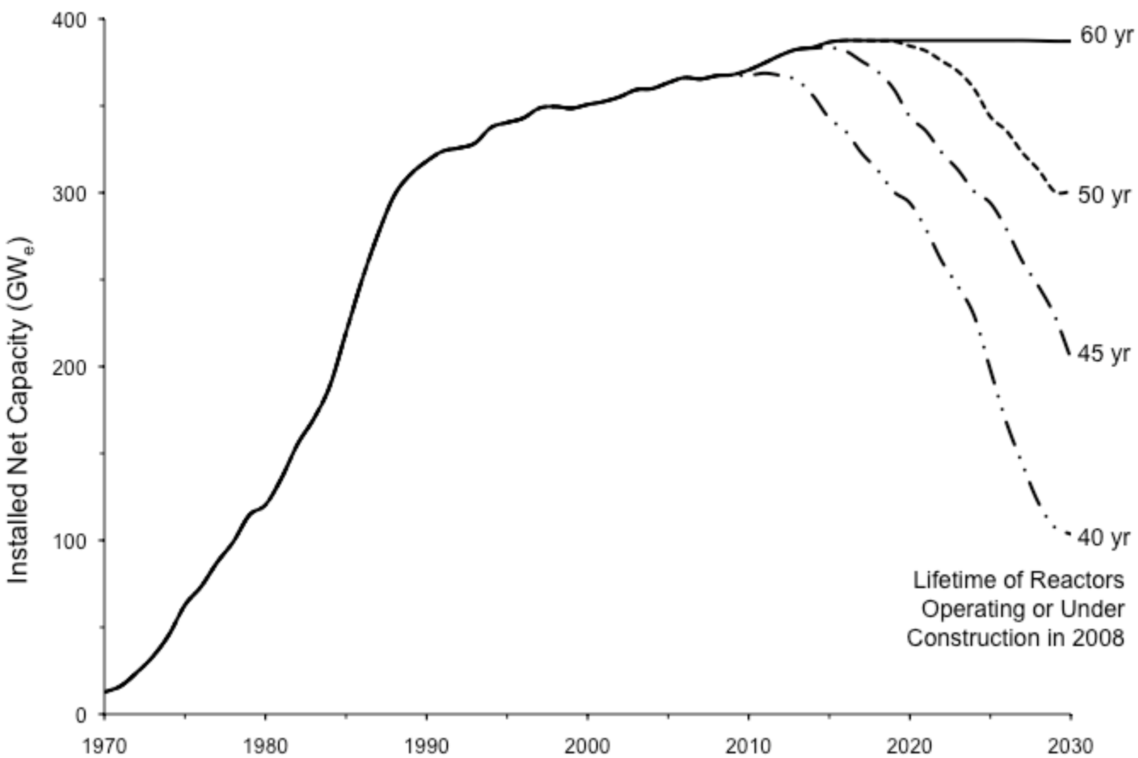
[3] Assumes that capacity increases from 367 to 390 GW_e and average capacity factor increases from 80 to 85 percent.
[4] Plant Life Management for Long Term Operation of Light Water Reactors, IAEA-TRS-448, IAEA, Vienna (2006).

U.S. reactors had received a license renewal, and the operators of most of the remaining reactors either had an application under review or indicated their intent to submit an application. In Japan and most European countries, reactors are licensed for an indefinite term, with safety reviews required every 10 years. Nuclear reactors have low fuel and operating costs—about $20 per megawatt-hour, or two to four times less than the cost of electricity from a new plant of any type. The additional cost of replacement power resulting from the premature shutdown a single large reactor is about $200-300 million per year.[5] Thus, there is a powerful economic incentive to extend the licenses of existing reactors. Only Germany and Belgium currently plan not to extend the operating lifetime of their reactors, and some observers believe this planned nuclear phase-out will be reconsidered in light of commitments to reduce carbon emissions.

Thus, a near-term decline in nuclear capacity cannot occur as a result of a failure to build new reactors. As shown in figure 3, a significant decline in nuclear generation by 2030 can occur only through the early shutdown of existing reactors combined with a failure to build sufficient replacement capacity. This has important implications for scenarios that postulate a substantial contraction of nuclear energy in the next twenty years.

Figure 3. The projected capacity of reactors operating or under construction in 2008, for operating lifetimes of 40 to 60 years.



Source: International Energy Agency, *Nuclear Power Reactors in the World* (Vienna: IAEA, 2008).

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[5] 1000-MWe reactor with 90% capacity factor with fuel/operating cost $25-40/MWh less than replacement power.

Table 1 gives the number and capacity of reactors that were operating or under construction in 2008, in order of a country's total operating capacity. The top three countries—the United States, France, and Japan—account for almost 60 percent of current world nuclear capacity; the top six account for 75 percent; the top ten, 86 percent. If world nuclear capacity declines significantly over the next 20 years, the decline must occur primarily in these countries.

Table 1. The number and net capacity of reactors operating or under construction in 2008.

	Number of Reactors		Net Capacity (GW_e)		Percent of Electricity Generation
	Operating	Under Construction	Operating	Under Construction	
United States	104	1	100.6	1.2	19%
France	59	1	63.3	1.6	77%
Japan	55	1	47.6	0.9	28%
Russia	31	7	21.7	4.7	16%
Germany	17		20.5		27%
South Korea	20	3	17.5	2.9	35%
Ukraine	15	2	13.1	1.9	48%
Canada	18		12.6		15%
United Kingdom	19		10.2		15%
Sweden	10		9.0		46%
China	11	6	8.6	5.2	2%
Spain	8		7.5		17%
Belgium	7		5.8		54%
India	17	6	3.8	2.9	3%
Czech Republic	6		3.6		30%
Switzerland	5		3.2		40%
Finland	4	1	2.7	1.6	29%
Slovakia	5		2.0		54%
Bulgaria	2	2	1.9	1.9	32%
Hungary	4		1.8		37%
South Africa	2		1.8		5%
Brazil	2		1.8		3%
Mexico	2		1.4		5%
Romania	2		1.3		13%
Lithuania	1		1.2		64%
Argentina	2	1	0.9	0.7	6%
Slovenia	1		0.7		42%
Netherlands	1		0.5		4%
Pakistan	2	1	0.4	0.3	2%
Armenia	1		0.4		43%
Iran		1		0.9	
World	433	33	367.3	26.7	14%

Source: International Energy Agency, *Nuclear Power Reactors in the World* (Vienna: IAEA, 2008).

Possible Causes of Contraction

Failure to adopt carbon mitigation policies. There is now a firm scientific consensus that anthropogenic greenhouse gas emissions have caused and will continue to cause changes in global climate. As a result, there is increasing international political consensus that significant near-term policy actions are required to limit greenhouse gas emissions in order to stabilize concentrations at levels that avoid highly disruptive changes in climate. The principal holdout has been the United States. The fact that President Obama advocates policies to reduce U.S. carbon emissions has led many observers to conclude that effective policies will soon be put into place.

The most frequently mentioned policy is a carbon cap-and-trade system, in which a cap on total annual emissions is established and permits for the right to emit carbon are bought and sold. Alternatively, a tax could be levied on carbon emissions. Although the cap or tax could be established for individual countries or groups of countries, stabilization would require participation and coordination by all major emitters. Most studies indicate that a price on the order of $25-50 per metric ton of carbon dioxide in 2030 would be required to achieve reductions in global emissions consistent with stabilization at an equivalent doubling of carbon dioxide.[6] This is equivalent to an increase of about $25-50 per megawatt-hour in the cost of electricity from a new coal-fired plant—an increase of 50-100 percent.[7] A carbon price at the lower end of this range would eliminate most or all of the current price difference between coal and nuclear; a price at the upper end of the range would give nuclear a clear economic advantage over coal.[8] Much of the talk about a "nuclear renaissance" is driven by anticipation of controls on carbon emissions.

Putting into place policies that impose substantial costs on carbon emissions is easier said than done. Developing countries, such as India and China, are unlikely to agree to bear these costs and thereby slow their economic growth. Recognizing that no carbon reduction regime can be effective without the participation of all major emitters, the United States is unlikely to impose meaningful controls on its own emissions without reduction commitments by developing countries. The solution lies in some combination of phased-in obligations for developing countries coupled with technical and financial assistance to facilitate their adoption of low-carbon technologies. Working all of this out in a manner that will acceptable to all or even most

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[6] Baker et al., "Mitigation from a cross-sectoral perspective," in B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer, eds., *Climate Change 2007:Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK: Cambridge University Press, 2007). For example, potential global reductions at a cost of $\$50/t_{CO_2}$ are estimated at 13-26 Gt_{CO_2} in 2030, 20-50 percent below the baseline level in 2030.

[7] Current coal-fired power plants emit about 1 t_{CO2}/MWh; higher efficiencies made possible by new plant designs should decrease this to 0.8 t_{CO2}/MWh by 2020-30. Combined-cycle gas-fired plants have equivalent CO_2 emissions of about 0.5 t_{CO2}/MWh, so a carbon price of $\$25\text{-}50/t_{CO2}$ would increase the cost of electricity by about $12-25/MWh, making nuclear more competitive with them, too, especially at higher gas prices.

[8] A coal plant could avoid a carbon tax by capturing and sequestering the carbon in the coal. The cost of capturing the CO_2 from current coal-fired plants is very high, but it could be much lower for new plants. Integrated gasification combined-cycle (IGCC) plants, for example, could produce a nearly pure stream of CO2 for disposal. Cost estimates for IGCC plants are uncertain, but are significantly higher than for current coal plants. The transport and sequestration of CO2, in depleted oil and gas wells or in deep saline aquifers, is technically feasible but adds additional costs. It is unclear whether a new IGCC plant with sequestration could compete economically with a new nuclear plant.

major emitters will not be easy. Allocating allowable annual emissions among countries, as was done on a modest basis for developed countries in the Kyoto Protocol, will be far more difficult for deep global reductions. This allocation can be avoided by establishing a global emission trading system, but not without raising a host of other problems that are no less intractable. And even if international negotiations are successful, difficulties can be anticipated in securing ratification and proper implementation by all major emitters.

It is possible—perhaps even likely—that attempts to establish an effective global carbon control regime will fail. If these efforts fail and carbon emissions have no cost in important electricity markets, current nuclear technologies could fail to gain a cost advantage over coal and natural gas. Although it is easy to see why this might dim prospects for nuclear growth, it should not cause a decline in nuclear energy production. As noted above, scenarios by the EIA, IEA, and IAEA show growth in world nuclear generation without additional carbon-reduction policies. In the EIA scenarios, for example, nuclear electricity generation increases by 30 to 60 percent from 2008 to 2030.[9] Thus, a failure to adopt a carbon-control regime is unlikely, by itself, to produce a decline in nuclear energy production by 2030.

Lower-cost alternatives. As noted above, a decline in nuclear generation by 2030 is possible only if most existing reactors operate for substantially less than 60 years. The cost of electricity from existing reactors is much less than the cost of electricity from a new plant of any type. There is little chance that any alternative electricity source would be able to compete economically with existing reactors in this time frame. Thus, there will be no economic incentive to shut down existing reactors before the end of their safe operating lifetime.

Indeed, if significant constraints are imposed on carbon emissions, new nuclear plants are likely to be built in many countries. Low-carbon alternatives to nuclear are limited and have significant drawbacks for baseload electricity supply. The potential growth of hydropower and geothermal is limited in many regions. The cost of wind-generated electricity may be less than nuclear capacity in some areas, but wind, which is intermittent, cannot substantially displace coal or nuclear for baseload power without backup generation, energy storage, or greatly enhanced transmission grids, all of which are expensive. Solar is similarly unsuitable for baseload generation, and is unlikely to be cheaper than new nuclear in the next 20 years. Biomass is unlikely to be more than a niche supplier of electricity due to the low energy density of biomass and thus the relatively high costs of transporting feedstock. Fusion, if it can be made to work, would be commercially available on a significant scale no earlier than 2050. The only low-carbon alternative that might compete with nuclear for baseload electricity supply before 2030 is carbon capture and sequestration.[10] Although future research might substantially lower the estimated cost of carbon capture and sequestration, it can only increase the cost of electricity from coal and natural gas and make nuclear relatively more competitive.

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[9] EIA, *International Energy Outlook 2008*.

[10] Some believe that nuclear will not (or should not) be economically competitive with the other low/no-carbon alternatives. See, for example, Helen Caldicott, *Nuclear Power Is Not the Answer* (New Press, 2007); Arjun Makhijani, *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy* (Takoma Park, MD: Institute for Energy and Environmental Research, 2007); Brice Smith, *Insurmountable Risks: The Dangers of Using Nuclear Power to Combat Global Climate Change* (RDR Books, 2006). This is a minority view.

There is considerable uncertainty in the cost of new nuclear reactors because the rate of new construction has been low over the last two decades. The costs of new reactors in the EIA, IAEA, IEA, and EU studies referenced above are based on vendor estimates, together with the actual costs of reactors completed in the last decade in France, South Korea, Japan, and China. Although some have cited the U.S. experience in the late 1970s and 1980s to suggest that nuclear costs might turn out to be much higher than currently estimated, much of that cost escalation was due to poor project management. Because several major reactor vendors remain in the market, competition should control costs. Some analysts have pointed to rising prices for steel and other construction materials as cause for concern, but commodities constitute only a few percent of the cost of a nuclear plant, and increased commodity prices will have an even greater impact on the cost of coal, gas, and wind power.[11] Finally, some have suggested that a continuing shortage of credit may make it difficult to finance capital-intensive projects, such as nuclear reactors. But all new baseload electricity generation is capital-intensive. If capital is unavailable for new generation capacity and electricity demand rises to exceed the available supply, electricity prices will increase to the point where the rate of return on investment in new capacity will be high enough to attract sufficient capital. Enthusiasm for new nuclear plants would be seriously dampened if new plants experience significant cost overruns and construction delays, but this is unlikely to apply to most vendors and most customers unless there are broader economic factors at play that would affect similar capital-intensive projects. And even if the first few new reactors are more expensive than expected, learning should bring down the costs of subsequent new plants, and any cost escalation that was driven by shortages of particular skills or equipment should stimulate supply and bring costs back down.

Decline in demand for electricity. Global energy demand is expected to double or triple over the next 50 years, driven by increases in population and per-capita income in developing countries. Demand for electricity is expected to grow even more rapidly; global consumption nearly doubles from 2005 to 2030 in the EIA reference case.[12] This increase in global electricity demand is a key factor in the forecasts for nuclear generation discussed above, which show growth in nuclear even without a carbon tax or permit system in place.

A major shock would be required to substantially reduce the forecasted increase in electricity demand. Even a deep global economic depression is unlikely to prevent growth in electricity consumption in many developing countries, where per-capita consumption currently is low and a significant fraction of the population is without service. The Great Depression may provide a useful point of comparison in this regard, because per-capita electricity consumption and the fraction of households without electricity service in the United States in 1929 is comparable to current levels in many developing countries.[13] U.S. gross national product fell over 30 percent from 1929 to 1933, but electricity consumption decreased by only 12 percent. Per capita income

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[11] According to Per Peterson, the materials in a 1000-MW_e pressurized water reactor contribute only \$36/kW_e to the capital cost at the high commodity prices prevailing in early 2008 (1-2 percent of the overnight construction cost).
[12] EIA, *International Energy Outlook 2008*.
[13] In 1929, per-capita U.S. electricity demand was 960 kilowatt-hours per year—about the same as in Egypt, Ecuador, Zimbabwe, or the combined average of India and China today. In 1930, 32% of the U.S. population (40 million) were without electricity service; this can be compared with 22% (40 million) in the Middle East, 44% (490 million) in India, and 62% (550 million) in Africa who are today without electricity service. There are about as many people in the world without electricity today as there were in 1930 (about 1.6 billion). Central Intelligence Agency, *The 2008 World Factbook* (Washington, DC: U.S. Government Printing Office, 2008).

did not recover to 1929 levels until 1940, but by that time electricity demand had grown by 12 percent over the 1929 level.[14] Even if electricity consumption fell as a result of an economic depression, nuclear generation would not necessarily decrease because the marginal cost of nuclear electricity is low compared to coal and gas.

Even a global pandemic or major conventional war is unlikely to depress electricity consumption. The worst pandemic in modern history, the Spanish Flu of 1918-19, had little lasting effect on global economic output or energy use despite afflicting 20 percent of the world's population and causing 50 to 100 million deaths.[15] (A correspondingly lethal pandemic in 2030, when the world's population will be 8 to 9 billion, would kill 200 to 500 million.) The world wars of the twentieth century were extraordinarily destructive, but world energy consumption was greater a few years after each war than before the war. Even in Europe, economic growth was postponed only about a decade by both wars. It would appear that only a catastrophe of unprecedented proportions, such as a nuclear war or the impact of an asteroid, would be certain to result in a substantial decrease in electricity consumption, and in those unfortunate circumstances electricity supply would be the least of humanity's worries.

In summary, normal economic and demographic forces are unlikely to result in a decline in nuclear electricity generation over the next 20 years, regardless of whether costs are attributed to carbon emissions or whether technical advances lower the costs of other low-carbon alternatives, and regardless of major shocks to the world economy.

Loss of confidence in nuclear energy. Economic factors usually are most important in determining investment decisions, but other factors can sometimes be decisive. For example, it is sometimes asserted that the inability to effectively manage nuclear wastes could impede the construction of new reactors, and even cause the premature shutdown of existing reactors. Similar concerns have been expressed about reactor safety, but short of exceptional events such concerns would not cause a contraction in nuclear power. Exceptional events that could have a profoundly negative impact on decisions to build new reactors or the continued operation of existing reactors include a serious nuclear accident; a terrorist attack against a nuclear facility; the theft or diversion of nuclear material; or the detonation of a nuclear weapon. Of these events, a reactor accident is most likely before 2030.[16]

Waste management. No country has yet demonstrated a complete program for the management of nuclear waste, including the disposal of spent fuel or high-level waste. In the United States, the planned Yucca Mountain repository remains embroiled in technical and political controversy. If the U.S. Department of Energy does not receive a license to operate the Yucca Mountain facility, the future of radioactive waste management in the United States would

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[14] Bureau of the Census, *History Statistics of the United States, Colonial Times to 1970* (Washington, DC: U.S. Department of Commerce, 1975), series A7 (population), F1 (GNP), S44 (electricity).

[15] John M. Barry, "1918 Revisited: Lessons and Suggestions for Further Inquiry," in Stacey L. Knobler, Alison Mack, Adel Mahmoud, Stanley M. Lemon, eds., *The Threat Of Pandemic Influenza: Are We Ready?* (Washington, DC: The National Academies Press, 2005).

[16] Although some knowledgeable people believe that the odds of a nuclear detonation is high over this period (and the odds of a terrorist attack on a nuclear facility or nuclear theft are presumably still higher), there is no reliable way to estimate the likelihood of the these events, which involve deliberate actions by terrorists or national leaders in circumstances that never before have occurred.

be plunged into uncertainty. In most other countries that operate nuclear reactors (Finland is a notable exception), waste management plans are less advanced; in most cases, plans have not been announced or potential repository sites have not been identified. Spent-fuel reprocessing, as currently practiced in France and planned in Japan, does not significantly reduce repository requirements. The United States, in partnership with Russia and other countries, has launched a program to transmute nuclear wastes, but this program would not eliminate the need for waste repositories.

Notwithstanding the technical controversy regarding the Yucca Mountain site, there is a firm international scientific consensus that, with proper site selection and repository construction, geological disposal of spent fuel and reprocessing wastes can be accomplished in a manner that would protect human health and environmental quality for the indefinite future. Although it is easy to envision the political difficulties involved in locating a repository in a particular place, it is difficult to see how such problems could result in a global contraction of nuclear power. Much of the new reactor construction forecasted for the next 20 years is in Asia, mostly in countries where there has been relatively less concern expressed about waste disposal. China is developing a repository in a very remote region of the Gobi desert that would have the potential for large capacity and is not likely to encounter political or technical difficulties. Although problems with Yucca Mountain might curtail plans for new nuclear reactors in the United States, it seems highly unlikely that this would be a global phenomenon.

It seems even less likely that waste disposal concerns would cause the shutdown of operating reactors. Although this possibility has been raised occasionally, this has been part of the political theater that accompanied difficult decisions to expand spent-fuel storage (in the United States) or to move forward with the operation of a reprocessing plant (in Japan). The marginal cost of electricity produced by an existing reactor is so low, and the costs and risks of dry-cask spent-fuel storage are so low, that it is inconceivable that significant numbers of existing reactors would be shut down prematurely solely because of waste management concerns. Should this prospect arise, another country might agree to store or dispose of the spent fuel. The Russian government has already expressed interest in receiving foreign spent fuel. Storage or disposal of foreign spent fuel could prove to be a highly lucrative business, because a reactor operator's willingness to pay for storage in order to continue the operation of a reactor would very substantially exceed the cost of providing the service.

Reactor accident. Unlike general concerns about nuclear safety or waste disposal, a major reactor accident has the potential to deliver a shock that could lead both to the discarding of plans for new reactors and to the early shutdown of many existing reactors. A "major" accident would include any event that results in a release of radioactivity large enough to cause deaths or radiation sickness due to high doses, or a large number of latent cancers due to lower doses. As illustrated by Chernobyl, it would not matter whether doses high enough to cause early illness or death were confined to plant workers or emergency responders. Indeed, as illustrated by the Three Mile Island (TMI) accident, it may not matter whether a significant amount of radioactivity is released, if the reactor is severely damaged and there existed the potential for a major release. Some might argue—as many did after the TMI accident—that a severe accident without a major release of radiation would demonstrate the safety of nuclear reactors, and thus would not undermine public confidence. This argument is unlikely to attract much support. Even today, nearly 30 years later, TMI remains a symbol of the dangers of nuclear energy. Even without a large release of radioactivity, a major accident would rivet public attention and make vivid the very real possibility of a truly devastating accident.

A major accident fairly likely in the next twenty years. There are 353 light-water reactors (LWRs) in operation and another 26 under construction. From today until 2030, these 379 reactors will experience 5500 to 7500 reactor-years of operation, depending on the operating life of the existing reactors. For existing LWRs, the probability of an accident that seriously damages the reactor core (a "meltdown") from all types of causes (except deliberate attack) is estimated at roughly 10^{-4} per reactor-year; the probability of a large release of radiation is about ten times smaller. (The probability of an accident at U.S., European, Japanese, and Korean reactors may be three to five times lower per reactor-year, but this is likely offset by higher risks in Russia, Ukraine, China, and other countries with a less-developed safety culture.) Thus, the probability of a core melt at an LWR before 2030 is on the order of 50%, and the probability of a major release is roughly 5-7 percent. In addition, to the LWRs, there are 16 Chernobyl-like reactors in Russia and Lithuania, and 18 older gas-cooled reactors in the United Kingdom, two fast-breeder reactors in France and Russia, and 44 heavy-water reactors in Canada, India, and five other countries. By 2030 these 80 reactors, which on average are less safe than the average LWR, will experience over 1000 reactor-years of operation, further increasing the likelihood of an accident.

A major accident would likely lead to a contraction of global nuclear energy production regardless of where the accident occurred. An accident in any country involving any type of reactor would deal a serious blow to plans to build all types of reactors everywhere. The exceptions might be countries, such as China and Russia, in which reactors are built and financed by the central government and where there is little or no public involvement in the decision-making process. Elsewhere, an accident in a light-water reactor in the United States, Europe, or Japan would have a larger impact than an accident in a Chernobyl-type reactor in Russia. If, for example, a serious accident occurred at an existing U.S. reactor, this would likely lead to the cancellation plans for new reactors as well as the termination of life-extension programs for many U.S. existing reactors. Claims that new designs would be more immune to accidents would fall on deaf ears.

Terrorist attack. A terrorist attack against a nuclear reactor could have a similarly negative effect on nuclear electricity generation, especially if it resulted in a significant release of radioactivity. As with a reactor accident, the mere occurrence of an attack is likely to be more consequential than its location or the exact circumstances surrounding the attack. An al-Qaeda attack against facilities in the United States, Europe, or Japan could be expected to have a greater impact on nuclear energy than an attack by Chechen or Kashmiri separatists on a Russian or Indian reactor, simply because the latter groups would not threaten facilities in other countries. That said, terrorist groups learn from each other, and a successful attack on a nuclear facility by one group could lead other groups to pursue similar tactics. The visibility and degree of success of the attack also would be important factors in determining the effect on global nuclear energy production. The crash of an aircraft into a reactor or an assault by a large group of heavily armed terrorists would have a greater impact than a thwarted sabotage attempt by insiders, the details of which might be suppressed.

A related event would be an actual or threatened military attack against an operating reactor. Pakistan, for example, might retaliate against Indian airstrikes on conventional military targets by threatening to attack an Indian power reactor, or North Korea might threaten to attack a reactor in South Korea or Japan. Such threats would lack credibility if the country making the threat was vulnerable to retaliation, and mere threats probably would not have a significant threat on the future of nuclear energy elsewhere. An attack would be judged to have a low probability of success, either because of defenses against air attack, the inaccuracy of ballistic missiles, and the hardness of a nuclear reactor. But an attack that resulted in a large release of radioactivity, or raised the prospect of a large release, could lead to a reexamination of plans to build or extend the life of reactors around the world.

Theft or diversion of civilian nuclear materials. Terrorists might steal nuclear materials or countries might divert materials and technologies from civilian nuclear facilities for military purposes. As with reactor safety, concern about theft and diversion are unlikely to have a significant effect on prospects for global nuclear energy unless an exceptional event focuses attention on the problem. One such event would be the theft of spent fuel or fresh mixed-oxide fuel by a terrorist group. If successfully stolen, either fuel could be used as the basis for a dirty bomb or as a source of plutonium to fashion a crude nuclear explosive. (The separation of plutonium from fresh mixed-oxide fuel would be substantially less challenging than the separation of plutonium from radioactive spent fuel.) Even if resulting contamination is limited (because the radioactive material in the dirty bomb is not efficiently dispersed or the crude device does not produce a nuclear explosion), or even if the detonation of the device in a city is only threatened but does not actually occur, we could expect such an event to have a substantial negative impact on the future of nuclear energy. A related type of exceptional event would be the diversion and rapid reprocessing of spent power reactor fuel by a country, with the separated plutonium used to build nuclear weapons. This could have a chilling effect on plans to build reactors in non-nuclear weapon states, and perhaps even the continued supply of fresh fuel for existing reactors.

Nuclear detonation. The most exceptional event of all would be the detonation of a nuclear device in a city. As with a reactor accident and a terrorist attack, it may not matter where or under what circumstances such a detonation occurs. Nor would it matter much whether the detonation was connected in any way with civilian nuclear energy. The detonation of a North Korean nuclear weapon on Seoul or a stolen Pakistani weapon on London, or the explosion of a crude nuclear device fashioned from high-enriched uranium stolen from a Russian military laboratory would be a momentous event for all things nuclear, including the continued operation and construction of nuclear reactors. The resulting humanitarian catastrophe would cause governments around the world to conclude that systems for managing nuclear risks were inadequate, resulting in a reexamination of all nuclear activities rather than only those aspects directly related to detonation. It is not difficult to imagine retrenchment among nuclear supplier countries, and popularly elected governments being pressured to abandon nuclear energy. Even well educated people often conflate and confuse the risks of nuclear weapons with those of nuclear energy, and the psychological trauma of a nuclear explosion could easily lead to a rejection of all things nuclear.

Consequences of Contraction

The foregoing discussion suggests that a global contraction of nuclear energy is not likely to occur as a result of normal economic forces or theoretical concerns about safety, waste, or proliferation. These concerns are, so to speak, already built into the price of nuclear power and incorporated in forecasts that show nuclear power at least holding its own over the next 20 years. If a contraction occurs, it is most likely to result from an exceptional event, such as a major reactor accident or significant incident of nuclear terrorism. The overall impact of such an event on global nuclear electricity generation could be substantial regardless of its location or the number of people harmed, so long as there existed the potential for significant loss of life.

It is reasonable to assume that an exceptional event would have greatest impact on nuclear generation in North America and the European Union, where governments are more sensitive to public opinion and electricity generation relies more heavily on private investment and deregulated markets. As shown in table 1, these countries are responsible for almost 70 percent of current global nuclear generation. Although projected growth in nuclear generation is modest in these countries over the next 20 years, the early shutdown of existing reactors in North America and Europe could greatly outweigh growth in generation elsewhere in the world. Conversely, unless the exceptional event occurs on their own territory, it is likely to have a smaller impact on nuclear generation in Russia and China, where public opinion and private investment is less important, and in Japan and Korea, where alternatives to nuclear are relatively more expensive.

Let us assume that the exceptional event is sufficient to cause a dramatic loss of confidence in nuclear energy in North America and Europe (perhaps with a few exceptions, such as France and some countries in eastern Europe), leading generators and investors to abandon interest in nuclear power and governments to adopt policies favoring a phase-out of nuclear generation. Plans to extend the life of current reactors are discarded and many plants are shut down before the end of their operating life, and orders for new reactors are cancelled. In Russia and Asia, existing reactors continue to operate but plans for new reactors are delayed. The scale of the global nuclear enterprise shrinks significantly and the geographic center shifts to the east.

As a result of a decline in the global demand for fresh reactor fuel, prices for uranium and enrichment services drop dramatically. Plans for expansion are cancelled, only the least-cost suppliers are able to remain in business, and there is consolidation among the remaining suppliers. Gaseous diffusion uranium enrichment plants in the United States and France are shut down and plans for new centrifuge plants cancelled, leaving Russia and Urenco (with facilities in Germany, Netherlands, and the UK) with over 90 of the world market. There would be a similar but less dramatic consolidation in uranium mining, with Canada, Australia, and Kazakhstan remaining the major suppliers, and high-cost suppliers, such as the United States, dropping out. Threatened enrichment and mining industries in the United States and elsewhere can be expected to appeal to their governments for protection from foreign competition, but the impact of the precipitating event on domestic politics, combined the poor long-term prospects of the industry in general and the fact that remaining suppliers include close allies of the United States, should inhibit protectionism.

Declining nuclear electricity production would also affect the back end of the fuel cycle. The shutdown of many existing reactors would create pressures to centralize spent fuel storage, as a cheaper and safer alternative to maintaining existing storage at shutdown reactors. This could facilitate the creation of international spent fuel storage and the possibility that countries with large central storage facilities, such as the United States, might agree to receive spent fuel from other countries.

A decline in nuclear power should decrease interest in reprocessing. The decline in the demand for and the cost of fresh uranium fuel would make the recovery of plutonium for recycle in light-water or breeder reactors even less economically attractive than it is today. Programs for separation and transmutation, which are premised on an expanding nuclear industry and the building and operation of a new generation of fast reactors, would be abandoned.

Public attitudes toward nuclear waste disposal have been inextricably linked to debates about the desirability of nuclear power. Government policies requiring a phase-out of nuclear power might end that debate. This might permit a political consensus to be achieved on dealing with a country's nuclear legacy, facilitating interim storage and permanent disposal of a now-finite quantity of spent fuel. Alternatively, obsessive fears of radiation triggered by a reactor accident or nuclear terrorism might increase public aversion to spent-fuel storage or geologic disposal and prevent such a consensus. This could lead to logjam, with reactors and fuel processing facilities shutdown and nuclear materials stranded at existing locations for many decades.

One might look to other industries that have experienced a precipitous decline to gain insights into the consequences of this scenario for the nuclear industry. The decline of the defense industry after the end of the Cold War might be one example, but except for the former Soviet Union the decline was relatively shallow (about 20% globally and 40% in the United States) and lasted only about ten years, after which arms production began to increase. Nevertheless, the end of the Cold War triggered a substantial and orderly concentration of the industry, with the top five companies doubling their share of world arms sales. The decline of U.S. railroads offers another analog. As market share of freight and passenger traffic declined, the number of operating companies decreased from 470 in 1950 to 40 in 1980 and 7 in 2005. Passenger-miles decreased 90 percent from 1944 to 1970, leading to the creation of a government-owned corporation (Amtrak) in 1971 to provide passenger service. The nuclear industry is different from the defense and railroad industries in many ways, but one could expect a decline to produce a similar concentration of business, as well as an increase in government regulation—and even government takeovers—in an attempt to manage competition and assure the supply of services.

A very different and more cautionary example is the decline of the U.S. and Soviet nuclear weapon complexes after the end of the Cold War. In both cases there was a dramatic decrease in production activity at most facilities and a disorganized—in some cases, chaotic—shutdown of operations. In the U.S., this left nuclear materials frozen in place for years while plans for clean up and consolidation were made. The situation was far worse in the former Soviet Union, where the collapse of the economy and lack of payments to nuclear facilities resulted in pervasive deterioration in infrastructure and in safety and security standards.

I have argued that the most likely cause of a decline in global nuclear electricity generation is a reactor accident or a terrorist attack. So long as this is not accompanied by a global economic collapse, there is little reason to believe that the civilian nuclear industry would be plagued by the same problems that affected the former Soviet nuclear weapons complex. First, a decline in nuclear generation is most likely to occur in the United States and Europe, which compared to Russia in the early 1990s have political institutions that are far more mature, resilient and capable of responding to a decline in the nuclear energy industry. Second, materials in the civilian nuclear industry are generally far less vulnerable to theft and far less dangerous if stolen than the highly enriched uranium and plutonium that was dispersed throughout the Soviet weapons complex. Fresh LEU fuel poses essentially no risk. High radiation doses render a spent fuel assembly difficult to successfully steal and process for 200 years after its removal from a reactor. Fresh fuels containing plutonium (MOX) or high-enriched uranium would be far more vulnerable to misuse, but these are much less common and there is little reason why a decline of nuclear electricity generation per se—or the events that precipitate that decline—should substantially affect our ability to control these and other materials.

On balance, the decline in demand for fuel cycle services and the resulting drop in prices should lead to consolidation of the industry. Consolidation, in turn, should improve prospects for international control of uranium production and enrichment. The management and disposition of spent fuel could be more problematic, particularly for countries with small nuclear power programs and no reasonable prospects for developing domestic geologic repositories. Although one could argue that internationalization would be more important for an expanding nuclear industry, the prospect of large future profits makes it more difficult to achieve. If nuclear generation declines, concerns about the economic impact of internationalization of fuel-cycle services become both less important and easier to manage.

Even if this true generally, there are likely to be exceptions, mostly likely in developing countries that today have less nuclear infrastructure, such as Argentina, Iran, or Pakistan. There may also be a strong desire in some cases to retain independent facilities that remain outside of international control, either to support a nuclear weapons program or the option to pursue such as program. But this is likely to true regardless of trends in nuclear generation elsewhere, and it is difficult to see how a decline in global nuclear generation could by itself have a substantial effect on such tendencies. Rather, the nature of event that precipitates this decline would be far more important in this regard. For example, the theft or diversion of material from a commercial facility leading to a nuclear detonation would create very strong pressure to consolidate materials and place them under international control. A reactor accident would not create such pressures.

The most important near-term consequence of a decline in global nuclear generation is likely to be a significant increase in the price of electricity in regions, such as northern and eastern Europe, Japan, and South Korea, where existing reactors that supply a significant fraction of electricity consumption may be shut down. As noted above, the marginal cost of electricity from existing reactors is low—two or four times less than the cost of electricity from the lowest-cost source of new capacity. If a carbon control regime is not in place, a phase-out of nuclear would almost certainly lead to an increase in the construction of coal-fired power plants and an associated increase in carbon emissions. If a carbon regime exists, a decline in nuclear would lead to a substantial increase in the carbon price. In either case, if the construction of new carbon-free non-nuclear capacity cannot keep pace with the shutdown of existing reactors, electricity supply shortages and large price spikes would ripple throughout the affected economies. The resulting economic and political effects of these shortages and price spikes could dwarf the direct effects on the nuclear industry.

The most important long-term consequence of nuclear contraction will likely be on the spread of nuclear technologies and the capability to produce nuclear weapons. Many countries that have recently expressed interest in acquiring nuclear reactors will abandon these ambitions, and the total number of countries with nuclear facilities may decline as some get out of the nuclear business altogether. The decrease in the demand for fuel will remove pressures to expand enrichment capacity and will remove the economic incentive for new countries to get into the enrichment business. Similarly, reprocessing and the use of plutonium fuels will become less attractive, reducing economic incentives to engage in these activities, even in countries with long-term plans to continue to operate nuclear reactors. As illustrated by Iran's nuclear program, some countries may pursue enrichment (or reprocessing) in order to acquire and maintain a capability to produce nuclear weapons. But such programs would be harder to defend in a world of nuclear contraction, making it easier to marshal coordinated international opposition.

A decline in the global nuclear industry would result in less investment in nuclear energy research and development, and less interest in developing a new generation of safer reactors and proliferation-resistant fuel cycles. On balance, however, overall accident and proliferation risks are likely to be lower in a world of declining nuclear power than in a nuclear renaissance. This is partly because fewer countries would operate reactors and have nuclear expertise, and because sensitive processes, such as enrichment and reprocessing, would be concentrated in fewer countries. One could expect a high level of technical assistance and international cooperation on safety and security at remaining operating reactors and spent-fuel storage sites after a major accident or terrorist attack, and a very high level of concern about theft or diversion after a nuclear explosion. Remaining reactors would almost certainly operate on a one-through fuel cycle, which is relatively invulnerable to theft or diversion and could be made more proliferation-resistant through the consolidation and internationalization of fuel supply and spent-fuel storage and disposal.

Avoiding and Mitigating Contraction

Because a contraction in nuclear energy is most likely to occur as a result of a reactor accident or nuclear terrorism, reducing the probability of accidents and terrorism is the best way avoid such a contraction. As regards reactor accidents, the most urgent task is to work to improve the safety culture in countries where it may be lacking, including peer review of safety assessments and emergency preparedness and programs to improve operator training and to upgrade safety systems. As regards nuclear terrorism, the most urgent task is to ensure that all weapon-usable materials (or materials from which they can be extracted, such as fresh MOX or aged or lightly-irradiated spent fuel) are subjected to very high levels of physical protection and security, comparable to that used to protect nuclear weapons. It would also be useful to adopt international standards for physical protection of nuclear facilities and to subject site-specific plans to peer review. Over the longer term, deep reductions in nuclear arsenals by the nuclear-weapon states, together with a serious commitment to pursue a global prohibition on nuclear weapons, could be vital to obtaining an international consensus on additional measures to reduce the risks of nuclear proliferation and nuclear terrorism, such as limiting the spread of enrichment and reprocessing facilities.

Many of these same measures would serve to mitigate some of the consequences of contraction, should it occur. Unfortunately, there is little that can be done today to mitigate the main short-term effect of a decline in nuclear energy generation—a shortage of electricity and resulting price increases.