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THE GROWTH OF NUCLEAR POWER:
Drivers and Constraints

Richard K. Lester
Robert Rosner

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292 Main Street, E38-104, Cambridge, MA 02139-4307
617-253-7522
web.mit.edu/ipc/www

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- Richard K. Lester <rklester@mit.edu>
- Robert Rosner <r-rosneruchicago.edu>

Richard Lester & Robert Rosner

The growth of nuclear power: drivers & constraints

Many countries around the world are taking a fresh look at nuclear power. An important cause of what has come to be called the global nuclear renaissance is the prospect of severe disruptions to the earth's climate brought about by continued increases in greenhouse gas emissions, primarily from the combustion of fossil fuels. Nuclear power occupies a unique position in the debate over global climate change as the only carbon-free energy source that is already contributing to world energy supplies on a large scale and that is also expandable with few inherent limits. These attributes are regularly highlighted by nuclear energy advocates and now, increasingly, by some formerly anti-nuclear activists, even as other environmentalists remain strongly opposed to this technology.

The list of countries in which nuclear expansion is being either vigorously pursued or at least seriously considered is long. Several countries in Asia and Eastern Europe with active nuclear power programs have recently announced plans to accelerate those programs. The most important case is China, whose gargantuan appetite for coal caused it recently to overtake the United States as the world's largest emitter of greenhouse gases. In anticipation of continued rapid economic growth and, to a lesser degree, to limit its fossil fuel consumption, last year the Chinese government announced its intention to double its previous target for nuclear power growth by the year 2020. Large numbers of new nuclear plants are also planned in South Korea, Japan, India, and Russia.

Elsewhere, in countries where an earlier wave of nuclear development faltered years ago and the prospects for new nuclear construction have long seemed dim, the terms of the debate have shifted, in some cases dramatically. In Sweden, the government recently decided to overturn a ban on new nuclear power plant construction that had been in effect since 1980. The U.K. government has announced its support for a large program of new nuclear power plant construction. Other European countries, such as Italy, Spain, and Belgium, are reassessing their current approach to nuclear power. Even in Germany, where for many years official policy has called for the phase-out of the country's nuclear power program by 2020, there appear to be growing doubts about the advisability of that policy. In the United States, where the last order for a nuclear power plant was placed more than 30 years ago, 17 applications to build 26 new nuclear power reactors had been filed with the Nuclear Regulatory Commission as of April 2009.

In addition, more than 25 countries—most of them emerging economies and several in the Middle East and North Africa—have recently declared an interest in nuclear power for the first time. Some are still in the early stages of considering the option, while others, including Turkey, Indonesia, and the United Arab Emirates, have moved some way toward building their first nuclear power reactors.

The International Atomic Energy Agency (IAEA) reports that 44 nuclear units, with a capacity of almost 40 GWe, are currently under construction. According to the World Nuclear Association, a trade group, at least 70 new units are being planned in the next 15 years worldwide, and another 250 units have been proposed, suggesting that from 470 gigawatts electric (GWe) to as much as 750 GWe will be in place by 2030,.

The lengthening list of countries with nuclear programs and plans is striking for its diversity. It includes advanced and developing economies, large and small countries, highly urbanized and sparsely populated countries, countries with a long history of nuclear development and countries with almost none, and countries with no indigenous energy resources and countries with extensive deposits of both uranium and fossil fuels. This diversity of national circumstances, when coupled with new technological developments in the nuclear energy field, opens up the possibility that the world's civilian nuclear industry will in the future develop along divergent pathways. This would be something of a departure from the recent past and raises a number of challenging questions for policy-makers, business practitioners, investors, and others.

In its earliest years, the nuclear power industry also seemed destined to develop along many different trajectories. Nuclear power reactor developers in Canada, the United Kingdom, France, the Soviet Union, Japan, and the United States each introduced a different type of nuclear power reactor technology. National strategies for the nuclear fuel cycle also differed significantly. Eventually, the light water reactor technology that was first introduced in the United States came to dominate the global nuclear power industry. Light water reactors now account for more than 90 percent of installed nuclear capacity worldwide, although today the leading suppliers of this technology are French and Japanese. (The only other power reactor technology with a significant market presence internationally has historically been the Canadian CANDU design.)

There is today a fairly high degree of uniformity in the nuclear plans and programs of most of the major nuclear countries, and nuclear power is one of the most highly globalized of all industries. The nuclear power plant supply industry is dominated

by a small number of large global suppliers of light water reactor equipment and technology. National regulatory standards and practices are harmonized to a substantial degree. National strategies for the nuclear fuel cycle are also aligned, and major fuel cycle service providers operate globally. And a new class of global nuclear power plant investor-operators is emerging, led by the French utility EDF, whose joint ventures with nuclear power companies in China and the United States, and its recent purchase of the U.K. nuclear operator British Energy, have established it as an important player in all of the world's largest nuclear power markets.

This global convergence has yielded a number of benefits, including economies of scale and accelerated learning. The case for international coordination and standardization of strategies and practices is further strengthened by the special care with which nuclear technology and materials must be handled, and the international consequences of local nuclear accidents or missteps. From time to time this strategic convergence has also served the purposes of nuclear industry leaders and government policy-makers, providing them with a sort of strength-in-numbers defense against local critics. A few years ago, when President George W. Bush announced his support for closing the nuclear fuel cycle in the United States, the new policy was welcomed by the French, British, and Japanese, in no small part because it seemed to legitimize their own longstanding commitment to a closed nuclear fuel cycle, including reprocessing and mixed-oxide fuel use. Thirty years earlier, when the United States abandoned its plans to reprocess spent nuclear fuel and sought to persuade others to do likewise as a nonproliferation measure, the outraged reactions from Europe and Japan were partly stimulated by a fear that the American policy reversal would give ammunition to

domestic critics of their own reprocessing plans, which they had no intention of abandoning.

The attractions of nuclear conformity remain strong today, yet the prospect of divergent development pathways may now be greater than at any time since the earliest days of the nuclear power industry. What are the implications of this for nuclear energy growth? How might it affect the course of international nonproliferation efforts?

* * *

The increased focus on nuclear energy is motivated by a wide range of other factors in addition to the very low carbon footprint, including:

- *Increasing energy and water demand, coupled with strained supply sources.*

Global population growth in combination with industrial development and expectations of rising living standards will lead to a doubling of worldwide electricity consumption by 2030. These pressures are also leading to shortages of fresh water, and increasing calls for energy-intensive desalination plants. Nuclear energy offers significant opportunities to meet the increasing requirements for electricity base load and to produce industrial-scale clean water.

- *Economics.* Until the onset of the global economic crisis, increasing fossil fuel prices had the effect of improving the relative competitiveness of nuclear power.¹

If, as seems probable, future carbon emissions will be taxed at progressively

¹ If the uncertainties in the credit markets persist, the economic competitiveness of nuclear energy will erode. Because of the high capital intensity of nuclear energy projects, the cost of nuclear electricity is particularly sensitive to the availability of financing at competitive rates.

higher rates, the effect will again be to strengthen the competitiveness of nuclear power.

- *Insurance against future price exposure.* A longer-term advantage of uranium over fossil fuels is the relatively small contribution of the former to the total cost of electricity, and thus the relatively low impact of increased uranium prices on electricity costs. This relative insensitivity to fuel price fluctuations offers a way to stabilize power prices in deregulated markets.
- *Security of energy supply.* Nuclear energy offers a hedge against the vulnerability to interrupted deliveries of oil and gas.

The specific reasons for the current nuclear revival vary by country. Population growth, accompanied by economic development, has led to strong growth in electricity demand in many countries. In some of these, a lack of fossil fuel resources has made nuclear an obvious choice to meet the new demand. In others where fossil fuels are abundant but relatively expensive, nuclear is seen as a hedge against further fuel price increases and price volatility, and sometimes as an enabler of greater export earnings from the domestic fossil endowment. For countries with no fossil fuels, nuclear is also cited as a form of insurance against supply or price disruptions. And in most countries, as we have already noted, climate change is a driver of the renewed interest in the nuclear energy option. That is certainly true of the United States, where the current talk of a nuclear energy renaissance would surely be more muted were it not for concerns over greenhouse gas emissions.

Many climate scientists have concluded that the worst risks of climate change might be avoidable if the atmospheric concentration of CO₂ can be kept below 550 parts per million (ppm), or roughly twice the pre-industrial level. The current CO₂ concentration is about 380 ppm, with smaller amounts of other, more potent greenhouse gases, such as methane and nitrous oxide, adding another 70 ppm of CO₂-equivalent. Emissions of greenhouse gases (GHGs) continue to rise, and the total GHG concentration is increasing at an accelerating rate—currently somewhere between 2 and 3 ppm per year.² In its latest assessment, the Intergovernmental Panel on Climate Change (IPCC) has estimated that a doubling of the atmospheric concentration of GHGs relative to the pre-industrial level would eventually (after a few centuries) cause an increase in the globally averaged surface temperature that most likely would fall in the range of 2 to 4.5°C, with a 50 percent probability of remaining below 3°C and a small but significant probability of exceeding 5°C. These are globally averaged figures, and expected temperature changes in large areas of the world would be substantially greater, accompanied by substantially greater local fluctuations.³

Some analysts, weighing the risks involved, have concluded that a 550 ppm limit on CO₂ concentration (corresponding to a total GHG concentration of about 670 ppm) would go beyond the bounds of rational risk-taking, and advocate a more restrictive limit. The European Union has adopted the goal of capping the expected equilibrium global average temperature at 2°C, corresponding to a stabilized GHG concentration of about 450 ppm

² Other anthropogenic activities, such as the release of aerosols, have a cooling effect, and the net warming effect of anthropogenic releases currently amounts to the equivalent of about 380 ppm of CO₂. Note that there is often confusion about the form in which these concentrations are expressed, that is, as CO₂ only, as CO₂ plus other GHGs, and as CO₂ plus other GHGs combined with the net cooling effect of aerosols.

³ How long before climate equilibrium is reached depends sensitively on the details of the scenario under which the atmosphere's GHG concentration finally equilibrates.

CO₂-equivalent. Since this level has already been reached (although the offsetting effect of aerosol cooling lowers the effective GHG concentration to about 380 ppm), the EU goal is extraordinarily ambitious and almost certainly unrealistic. Most policy-level discussions are currently focused on CO₂ stabilization targets in the 450 to 550 ppm range, even though the scientific consensus is that significant ecological and economic damage is very likely at such levels. Yet even the upper end of this range will be extremely difficult to achieve. The world relies on fossil fuels for more than 80 percent of its primary energy supplies today, and under “business as usual” conditions, annual energy-related CO₂ emissions (which account for a large fraction of the world’s GHG emissions) would likely increase threefold by the end of this century.⁴ This in turn would imply atmospheric CO₂ concentrations in the 700 to 900 ppm range by the year 2100, with the expected global average temperature increase eventually exceeding 6°C. There is thus a large gap between business-as-usual projections and what will be required to reduce the risk of climate change.

To remain below the limit of 550 ppm, global emissions would have to peak in the next 10 to 20 years, and then fall to a level well below year 2000 emissions. Equity considerations will require that wealthy countries accept higher targets for emissions cuts than poor countries, and several recent reports have called for reductions of 60 to 80 percent in the advanced countries by the year 2050. President Obama recently called for a reduction in U.S. carbon emissions of more than 80 percent by the year 2050. Such cuts are likely to require even greater reductions in the power sector because in other sectors

⁴ L.E. Clarke, J.A. Edmonds, H.D. Jacoby, H.M. Pitcher, J.M. Reilly, R.G. Richels, “Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations”, Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Climate Change Research, U.S. Department of Energy (2007).

the maximum achievable reductions may be smaller. A key question here will center on the transportation sector, and how rapidly that sector can be weaned off liquid fossil fuels via some combination of (renewable) advanced biofuels and plug-in (hybrid) technologies.

Stabilizing the CO₂ concentration in the 450 to 550 ppm range will require rapid, large-scale decarbonization of the global energy supply system beginning, in effect, immediately, combined with vigorous and continuing worldwide improvements in the efficiency of energy use. The longer the delay in embarking on this path, the more difficult it will be to achieve the end goal. Because carbon dioxide molecules released into the atmosphere stay there for about a century on average, a ton of carbon emitted today will have roughly the same effect as a ton emitted at any time over the next several decades. So it is appropriate to think of a global, intergenerational “budget” of carbon emissions that corresponds to a given stabilization target. The more of the emissions budget that is used up in the near term, the steeper and more painful the cutbacks in emissions will have to be in later years. What happens during the next few decades is therefore likely to be decisive. If, by the end of this period, the link between economic activity and carbon emissions has not been broken and if significant progress toward decarbonization of global energy supplies has not been made, the world will have lost almost all chance of avoiding serious and perhaps catastrophic damage from global climate change. It is also important to recognize that we will not be bailed out in this timeframe by laboratory breakthroughs that have yet to be made. Most of the heavy lifting during the next few decades will have to come from low-carbon energy systems whose attributes are already fairly well understood, if not yet commercialized.

Current trends are not encouraging. In the first half of this decade, the carbon intensity of the global energy supply system actually increased, reversing an earlier declining trend.⁵ Extraordinary efforts will be required to achieve significant decarbonization of energy supplies by mid-century, with all low-carbon energy sources and technologies—solar, wind, geothermal, biomass, nuclear, and coal use with carbon capture and storage—likely to be needed on a large scale. In each case, formidable technological, economic, and institutional obstacles stand in the way of scale-up, and there are no guarantees that they will be overcome. If any one of these technologies—including nuclear—were to be taken off the table, the difficulty of achieving the climate stabilization target would be much greater still. This is the strongest argument for nuclear power.⁶

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The contribution that nuclear power will actually make to reducing carbon emissions over the next few decades depends upon how rapidly it can be scaled up, and recent history is sobering. The existing global fleet of 436 commercial nuclear power reactors, with a total net installed capacity of about 370 GWe, provides about 16 percent of the world’s supply of electricity today. Depending on how the accounting is done, the emissions avoided by the nuclear fleet amount to about 650 million tons of carbon per year, or 9 percent of the

⁵ Michael R. Raupach et al, “Global and Regional Drivers of Accelerating CO₂ Emissions,” *Proceedings of the National Academy of Sciences of the United States of America* 104 (2007): 10288–10293.

⁶ To be specific, for nuclear energy to be a “game changer” in bringing emissions down to these levels, nuclear energy would need to be the key backbone for the electrical grid to: (1) power homes, businesses, and factories so that the economic growth prospects for both the developed and developing world are robust; (2) provide the electricity for plug-in hybrids and all other electric vehicles as a replacement for fossil fuels; and (3) enable the production of clean water, hydrogen, and other byproducts such as process heat for large manufacturing operations.

current global emissions total.⁷ But it has taken about 40 years for the nuclear industry to reach this level, and in the future the rate of expansion will need to be much faster if nuclear is to play a significant role in reducing carbon emissions. In business-as-usual scenarios published by the International Energy Agency and separately by the IPCC, CO₂ emissions are expected to reach about 41 gigatons (GT) per year (that is, 45 percent above today's level) by 2030 and perhaps 45–50 GT (60–80 percent above today's level) by 2050.⁸ If new nuclear power plants were called upon to eliminate, say, 25 percent of the increase in CO₂ emissions that would otherwise occur in these business-as-usual scenarios, roughly 700–900 GWe of new nuclear capacity would have to be added by 2050.⁹ In other words, in order to achieve the goal of displacing one quarter of the projected increase in carbon emissions, at least twice as much nuclear capacity would have to be built in the next 40 years as was built in the last 40. In fact, since many existing nuclear plants will reach the end of their useful life during this period and will have to be replaced, the actual requirement would be closer to three times the earlier result.

Circumstances can easily be imagined in which the call on nuclear would be greater still, since it is far from clear that the other non-fossil energy sources will be able to grow as rapidly as would be required to meet the other 75 percent of the carbon displacement target. (However ambitious these nuclear growth scenarios might seem, the growth requirements for other non-fossil energy sources are at least as challenging.)

⁷ This calculation assumes that the nuclear plants displaced coal-fired plants. The avoided emissions from the equivalent amount of natural gas fired capacity would be about 40% of this total.

⁸ For the former figure, see *World Energy Outlook 2008* (International Energy Agency, 2008). For the latter figure, see Fig. 3.9 of Working Group III Report, "Mitigation of Climate Change," from the *Fourth Assessment Report* (Intergovernmental Panel on Climate Change, 2007).

⁹ Assumes that these nuclear plants displaced coal-fired electricity generation.

Moreover, by mid-century the global rate of carbon emissions will probably need to be well *below* its current level in order to achieve an eventual CO₂ stabilization goal of 550 ppm, in which case the demand for all low-carbon sources, including nuclear, will be even greater.

In short, much may be riding on how rapidly nuclear power can be scaled up. If so, we will have to act fast—probably even faster than at the height of the first nuclear expansion. But this kind of expansion is currently blocked by a thicket of obstacles, and if the pace of nuclear growth is to accelerate, the characteristically long cycle times in the nuclear power industry—that is, the time it typically takes to move from initial planning of a new investment in a nuclear power plant or fuel cycle facility to the start of operation—will have to be reduced. But how realistic is this?

Many of the reasons for the long lead-times in the nuclear power industry are familiar and long-standing: protracted siting and licensing proceedings; underlying concerns over nuclear safety and waste disposal and, in some cases, nuclear proliferation; and the high costs of nuclear investments. Other problems have emerged more recently. The worldwide financial crisis has greatly complicated the prospects for financing capital-intensive projects of all kinds, including nuclear power plants. Moreover, the global industrial infrastructure required to support essential elements of nuclear power construction is at present inadequate to meet the needs of a broad nuclear power resurgence. For example, there is at present just one global supplier of the ultra-large forgings needed to make major nuclear components such as reactor pressure vessels, and the waiting list for delivery of these components has been lengthening. The electric grid infrastructure in many parts of the world is currently unable to support the deployment of large nuclear power plants. Serious shortages of human capital are also in prospect, and

will be exacerbated by the approaching retirement of many highly educated and trained nuclear specialists whose careers began during the first wave of nuclear growth in the 1960s and 1970s. There is a pressing need to attract high-quality students into the nuclear engineering discipline in order to support the growing needs for new power plant design, construction, and safe, efficient, and reliable operation. Similarly, the stringent quality demands associated with the construction of nuclear plants and their supporting infrastructure call for a highly trained trades workforce, which today is seriously depleted and must be rebuilt worldwide.¹⁰

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How these obstacles to nuclear expansion are dealt with will depend on particular national circumstances, which, as already noted, vary widely from one country to another. Moreover, the extent of these differences is likely to grow since more and more countries are likely to be involved. When national population and economic growth trends are taken into account, the unavoidable conclusion is that the group of countries relying heavily on nuclear power will need to expand considerably if nuclear is to make significant contributions to greenhouse gas reductions. An earlier MIT study showed that it will be effectively impossible to achieve an overall level of nuclear deployment large enough to make a significant contribution to reducing greenhouse gas emissions unless all four of the following developments occur¹¹: (1) continued large-scale nuclear

¹⁰ The difficulties recently encountered by the French firm AREVA in building a nuclear plant in Finland, the first in a new generation of large pressurized water reactors, are a reminder of how important the availability of highly trained trades, including civil construction, is to keeping this type of project on budget.

¹¹ *The Future of Nuclear Power: An Interdisciplinary Study* (Massachusetts Institute of Technology, 2003).

development in Japan and the other advanced economies of East Asia; (2) a renewal of nuclear investment in Europe; (3) a revival and major expansion of nuclear power in North America; and (4) significant programs in many developing countries, not just China and India, but also other populous countries like Brazil, Mexico, Indonesia, Vietnam, Nigeria, and South Africa.

It is difficult to exaggerate the contrasts between these countries in terms of nuclear capabilities, expectations, and requirements. The most highly evolved nuclear program today is that of France, where 58 nuclear power reactors account for almost 80 percent of that country's electricity supply and more than 40 percent of total primary energy production. In France, the use of nuclear power for conventional electricity generation is now approaching a limit set by the operational constraints of electric power systems. The available nuclear capacity exceeds the total base-load demand for electricity, and many French nuclear power plants are now operated at less than full capacity at certain times of the day and year. For highly capital-intensive facilities such as nuclear plants this is economically sub-optimal. French nuclear planners are exploring the feasibility of using surplus nuclear electricity to displace petroleum use in the transportation sector.¹² Initially the nuclear electricity produced during off-peak periods would be used to produce hydrogen via electrolysis of water. The hydrogen would be combined with biomass and nuclear heat to produce liquid fuels for cars and light trucks. Alternatively, the electricity could be used directly for plug-in hybrid electric vehicles. Subsequently, dedicated base-load nuclear plants could be built to provide hydrogen and

¹² We are grateful to Charles Forsberg for drawing this to our attention. See also Charles W. Forsberg, "Meeting U.S. Liquid Transport Fuel Needs with a Nuclear Hydrogen Biomass System," *International Journal of Hydrogen Energy* (forthcoming).

process heat for liquid fuels production on a larger scale. This is an interesting possibility since the eventual contribution of nuclear power to carbon emission reductions will depend in part on whether its role in supplying traditional electricity markets can be augmented by displacing petroleum use in the transportation sector. Other unconventional uses of nuclear energy under active development include seawater desalination¹³ and the extraction of oil from tar sands. In both cases, fossil fuels currently provide the heat source for the process. Nuclear desalination projects have been implemented in Japan, India, and Kazakhstan, and several new projects—some of them involving cogeneration of electricity and potable water—are under consideration in the Middle East and elsewhere.

For the time being, however, the primary role of nuclear power will continue to be the production of base load electricity. Here there are two possible directions of development. The first is a continuation of the long-term trend toward international convergence around standardized nuclear power reactor technologies, fuel cycle strategies, and operating and regulatory procedures. The benefits of this approach are most clearly discernible in the case of France, whose sustained commitment to a highly centralized program of progressively larger, standardized nuclear power plants supported by a closed nuclear fuel cycle has yielded what by most estimates is the world's most successful nuclear power program. The U.S. nuclear industry, which eschewed this approach in the past, has gradually been moving in this direction, overhauling (and standardizing) reactor control systems for existing plants, with the aim of simplifying

¹³ Argonne National Laboratory is completing a detailed cogeneration study in Jordan. The study team found that, because of the significant demand for clean water in the region, cogeneration is a viable economic approach.

operator training and reducing operator error. This approach, together with extensive preventive maintenance programs, has led the U.S. nuclear industry over the past two decades to outstanding performance in both human safety and reactor availability (presently averaging well over 90 percent). Thus one way to reduce cycle times (and, as a side benefit, significantly improve performance) is for everyone to pull in the same direction.¹⁴ And, indeed, broadly speaking this is where we are today. There are certainly important, unresolved questions about the distribution of fuel cycle facilities, especially the sensitive ones, but the basic pathway of nuclear energy development is relatively well defined. It is less clear whether this approach would be successful in the relatively large number of countries that may take up nuclear power on a significant scale for the first time, however, and for this reason, among others, we need to consider the other possible direction of development: the emergence of multiple nuclear development pathways, tailored to individual national circumstances.

The history of nuclear energy development teaches us that this technology has placed formidable demands on those institutions responsible for managing, regulating, financing, and overseeing it, and that the characteristically long cycle times in the industry—and, when they have occurred, its performance problems—can be attributed more or less directly to those heavy institutional demands. The question is whether alternative developmental strategies can be designed that would pose fewer such demands, and hence offer the prospect of more rapid scale-up. A “technocratic fix” for all of these

¹⁴ Unfortunately, at the moment the U.S. nuclear utilities are pulling in five separate directions with their design choices: the ABWR (Hitachi-GE) and ESBWR (GE) for boiling water reactors and the EPR (UniStar), AP-1000 (Westinghouse), and APWR (Mitsubishi) for pressurized water reactors.

problems is, of course, unrealistic. On the other hand, some configurations of nuclear technology are likely to be less burdensome to their attending institutions than others.

If a nuclear development strategy could be designed to minimize these burdens, and so reduce nuclear cycle times, what criteria would it need to satisfy?

- The first such attribute is cost-effectiveness. From the customer's perspective, a nuclear kilowatt-hour is indistinguishable from a solar or coal kilowatt-hour, so nuclear power must be economically competitive.
- Second, these nuclear systems would rely as much as possible on passive design features to ensure their safety, as opposed to active safety systems requiring intervention by human agents or (more likely) automatically controlled engineered systems.
- Third, such systems would minimize the risk of nuclear theft and terrorism, and also of state-level nuclear weapons proliferation.
- Fourth, on the question of scale (as opposed to scale-up), these systems would be appropriate to the scale of the national electricity grid and other relevant institutional capabilities.¹⁵
- Finally, any alternative nuclear development pathway would need to be evolutionary, rather than a disruptive, radical shift. The urgency of scale-up is

¹⁵ For example, building gigawatt-scale nuclear plants assumes the presence of an appropriately scaled electric grid infrastructure. If this is not present (as it is not in many developing countries), then one needs to turn to different technologies, namely, grid-appropriate (modular) nuclear reactors. However, the economics needs to be carefully considered here. In a recent Argonne study for a small developing country considering nuclear energy, we found that when the 'overnight' capital cost increased to \$3,500/kW or higher, the economic viability would be reduced substantially. Lower overnight costs are more likely for plants that have already paid down their first-of-a-kind engineering costs.

such that only technologies that have either already been tested in the marketplace or at least are close to commercial demonstration could be eligible for consideration.

If these are indeed desirable attributes for alternative nuclear pathways, the obvious place to begin planning new development strategies is to create the best possible story for the open fuel cycle; that is, we should start with what we have, and invest in ways to improve it in terms of cost, safety, environmental concerns, nonproliferation concerns, and scale. This suggests a number of actions. First, we could develop an explicit strategy for dry surface storage of spent fuel for several decades (at both on-site and centralized off-site locations). There are U.S. locations that, with local support, are volunteering as candidate off-site storage sites; we also need a more robust budgetary and management system, probably with very active nuclear utility involvement. Second, we could move toward the development of alternative spent-fuel disposal techniques that scale well for small nuclear programs, that are less expensive than the current mined geologic repository technology, and that are less demanding in their geological requirements. As an example, the deep borehole technology now under active consideration in Europe and elsewhere may meet all of these requirements. Third, we could focus on power plants that are smaller, that rely to a greater degree on passive safety,¹⁶ and that can be built with greater reliance on modular construction techniques. Fourth, we could explore once-through fuel cycles that are designed specifically for direct disposal and proliferation

¹⁶ An alternative is to focus on greater safety system redundancies; but we would argue that ultimately the better approach is to go for technologically simpler and inherently passive safety designs.

resistance (by, for example, substantially increasing the fraction of fuel actually burned in a once-through cycle).¹⁷

The one remaining area of uncertainty—related to a possible fifth response—is the long-term uranium fuel supply. The latest edition of the so-called Red Book, the authoritative biennial report produced jointly by the Nuclear Energy Agency of the OECD and the International Atomic Energy Agency, estimates that the identified amount of conventional uranium resources that can be mined for less than \$130 per kilogram is 5.5 million tons, but world uranium resources in total are expected to be much higher. Based on geological evidence and knowledge of unconventional resources of uranium, such as phosphates, the Red Book considers that more than 35 million metric tons will be available for exploitation. Given that in the entire 60-year history of the nuclear era the total amount of uranium that has been produced adds up to about 2.2 million metric tons, the availability of uranium is evidently not a limiting factor at this stage of nuclear power development. For time scales stretching to the end of this century and beyond, the situation may be different. On that time scale there are two options (not mutually exclusive) for dealing with potential uranium constraints: first, closing the fuel cycle so as to achieve very high (for example, above 90 percent) burnup; second, embarking on an aggressive program to improve the ability to locate and recover uranium resources economically. A life-cycle economic analysis for waste disposal will be needed to determine the efficacy of closing the fuel cycle at that time. If closing the fuel cycle is economically sensible, then any fuel supply problems will be solved as a by-product. A

¹⁷ Some have argued that the Department of Energy should switch gears: the rush to full-scale fuel reprocessing should be replaced with a more robust research program to develop new recycling technologies.

potential backstop for both options is the recovery of uranium from seawater. Currently, only Japan is pursuing this option in a significant way, and Japanese researchers are advertising a present-day recovery cost of \$1,000 per kilogram. That is an order of magnitude more expensive than standard uranium production costs, but the Japanese experience suggests that an eventual goal of \$150 per kilogram may be achievable. Since natural uranium currently accounts for only 3 percent of the total cost of nuclear generation, even \$300 per kilogram would be attractive and well below the break-even cost for competition with a mixed-oxide fuel cycle scheme with plutonium recycle in light water reactors or with fast burner reactors.¹⁸

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The issues we have outlined here are generally well understood within the energy, technical, and policy communities; but it is unfortunately also true that nuclear energy policies, as they have been implemented both in the United States and abroad, have been largely at odds with these considerations. Given the urgency imposed by the threat of climate change, by strong increases in energy demand worldwide, and by concerns related to energy security, it is high time that public policy and our technical understanding of the nuclear energy challenge are brought into alignment. This is the intent of our paper. In the end, the public policy and technical communities are on a joint

¹⁸ Note, however, that one would build breeders only if there is an economic argument for them—and that argument is not related to the cost of nuclear fuel, but is instead related to the financial and political costs of alternative nuclear-waste storage strategies.

learning curve: “For the things we have to learn before we can do them, we learn by doing them.”¹⁹

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Richard Lester is founding director of the Industrial Performance Center and professor of nuclear science and engineering at the Massachusetts Institute of Technology. His books include *Making Technology Work: Applications in Energy and the Environment* (with John Deutch, 2004), *Innovation: The Missing Dimension* (with Michael J. Piore, 2004), and *The Productive Edge: How U.S. Industries are Pointing the Way to a New Era of Economic Growth* (1998).

Robert Rosner, a Fellow of the American Academy since 2001, is the William E. Wrather Distinguished Service Professor in the Departments of Astronomy & Astrophysics and Physics at the University of Chicago. Previously he served as president of UChicago Argonne, LLC, and director of Argonne National Laboratory. He recently coedited *The Solar Tachocline* (with David W. Hughes and Nigel O. Weiss, 2007).

¹⁹ Aristotle, *The Nicomachean Ethics*, Book II, translated by William David Ross, first published in 1908, republished in 2007 at www.forgottenbooks.org.