Game Changers for Nuclear Energy

Kate Marvel and Michael May

AMERICAN ACADEMY OF ARTS & SCIENCES

Game Changers for Nuclear Energy

Please direct inquiries to:
American Academy of Arts and Sciences
136 Irving Street
Cambridge, MA 02138-1996
Telephone: 617-576-5000
Fax: 617-576-5050
Email: aaas@amacad.org
Web: www.amacad.org

Game Changers for Nuclear Energy

Kate Marvel and Michael May

Copies of this publication can be downloaded from:
http://www.amacad.org/publications/Changers.aspx.

Suggested citation: Kate Marvel and Michael May, *Game Changers for Nuclear Energy* (Cambridge, Mass.: American Academy of Arts and Sciences, 2011).

Cover image: Cooling towers in Weisweiler, North Rhine-Westphalia, Germany.
Image © Creativ Studio Heinemann/Getty Images.

ISBN#: 0-87724-091-4

This paper is part of the American Academy's Global Nuclear Future Initiative, which is supported in part by grants from Carnegie Corporation of New York, the William and Flora Hewlett Foundation, the Alfred P. Sloan Foundation, the Flora Family Foundation, and Fred Kavli and the Kavli Foundation. The statements made and views expressed in this publication are solely the responsibility of the authors and are not necessarily those of the Officers and Fellows of the American Academy of Arts and Sciences or the foundations supporting the Global Nuclear Future Initiative.

Contents

Acknowledgments

The devastating earthquake and tsunami off the coast of Japan in March 2011 will have a significant impact on the future of nuclear energy. The ultimate outcome of the Fukushima Daiichi accident will influence public opinion and government decisions about the future development of nuclear power worldwide. And the lessons we learn from the crisis will inform future decisions about nuclear fuel storage, appropriate safety standards and accountability measures, and emergency preparedness. However, our ability to respond effectively to the challenges presented by the Fukushima Daiichi accident has been, in large part, predicated on research, practices, and policies developed over the last three decades. What additional events or developments might surprise us in the future that could affect the spread of nuclear energy? How can we better anticipate such surprises so that we can more effectively mitigate the impacts of negative developments and maximize the impact of positive developments?

Toward this end, in August 2010 the American Academy, as part of its Global Nuclear Future Initiative, cosponsored a meeting with the Center for International Security and Cooperation (CISAC) at Stanford University on Game Changers for Nuclear Energy. The conference brought together a small group of representatives from diverse energy backgrounds—including government, industry, NGOs, national laboratories, and academia—for an in-depth discussion of variables that could affect the future of nuclear power. These include reactor and fuel cycle technology and regulation, accidents and security incidents, climate change, and relevant politics. The purpose of the workshop was to explore what events, foreseen or not, could change the presently foreseen nuclear power "game." What follows is the resulting paper from this meeting.

This Occasional Paper is part of the American Academy's Global Nuclear Future Initiative, which examines the safety, security, and nonproliferation implications of the global spread of nuclear energy and is developing pragmatic recommendations for managing the emerging nuclear order. The Global Nuclear Future Initiative is supported by generous grants from Carnegie Corporation of New York; the William and Flora Hewlett Foundation; the Alfred P. Sloan Foundation; the Flora Family Foundation; and Fred Kavli and the Kavli Foundation. The American Academy is grateful to the principal investigators of the Global Nuclear Future Initiative—Steven Miller, Scott Sagan, Robert Rosner, and Stephen Goldberg—for contributing their time, experience, and expertise to the work of the Initiative.

CISAC would like to thank the Flora Family Foundation and the John D. and Catherine T. MacArthur Foundation for supporting the scholars' work on this project.

We would like to thank Thomas Isaacs, Michael May, and Kate Marvel for organizing a substantive meeting and the participants for their thoughtful contributions at the meeting and to this paper. We are grateful to Michael and Kate for bringing their knowledge and insight to bear on this important issue.

Leslie Berlowitz
President and William T. Golden Chair
American Academy of Arts and Sciences

Scott D. Sagan
Caroline S.G. Munro Professor of Political Science
Codirector, Center for International Security and Cooperation,
Stanford University

Game Changers for Nuclear Energy

Kate Marvel and Michael May

Anticipating the future is difficult in any situation, but assessing the prospects for nuclear power in the next fifty years presents especially complex challenges.[1] The public perception of nuclear power has changed and continues to change. Once viewed as a miracle of modern technology, nuclear power came to be perceived by many as a potential catastrophe; now it is viewed as a potential, albeit potentially still dangerous, source of green power. Conventional wisdom in the 1960s held that nuclear power could dominate the electricity sectors of developed countries, while less than twenty years later, many predicted the complete demise of the U.S. nuclear industry following the Three Mile Island accident in 1979. Yet neither attitude fully forecast the situation today: a nuclear industry that is not dominant, but is far from dead. Indeed, the history of long-range planning for nuclear power serves as a caution for anyone wishing to make predictions about the state of the industry over the next half-century. Nonetheless, it is critical to assess its role in the future energy mix: decisions taken now will impact the energy sector for many years. This assessment requires both a review of past planning strategies and a new approach that considers alternate scenarios that may differ radically from business as usual.

While a number of studies have explored the future of nuclear power under various circumstances,[2] the purpose of this paper is to consider game-changing events for nuclear energy. We take "the game" to be the current

1. This paper is based in part on a workshop held at Stanford University's Center for International Security and Cooperation (CISAC) on August 26–27, 2010, in collaboration with the American Academy of Arts and Sciences. Workshop participants are listed at the end of this volume, and some of the workshop presentations are available at http://stanford.edu/group/gamechangers/. The workshop was conducted on a no-attribution basis. The authors are grateful to all workshop participants and to the leaders of the American Academy's Global Nuclear Future Initiative for their involvement and support of this project.

2. See, for example, "The Power to Reduce CO2 Emissions: The Full Portfolio–2009 Technical Report," EPRI Report 1019539 (Palo Alto, Calif.: Electric Power Research Institute, October 2009); "Prism/MERGE Analyses: 2009 Update," EPRI Report 1020389 (Palo Alto, Calif.: Electric Power Research Institute, July 2009); Leon Clarke and John Weyant, "Introduction," in "International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22," ed. Leon Clarke, Christoph Bohringer, Tom F. Rutherford, special issue of *Energy Economics* 31 (supp. 2) (2009): S63; *Nuclear Power and Climate Change* (Nuclear Energy Agency/Organisation for Economic Co-operation and Development, 1998); *Nuclear Energy Outlook* (Nuclear Energy Agency/Organisation for Economic Co-operation and Development, 2008); *Nuclear Energy in Perspective* (Nuclear Energy Agency/Organisation for Economic Co-operation and Development, November 2010).

no-surprise scenario for the next fifty years: that is, a slow and uneven growth in nuclear power worldwide. Growth will be very strong in China and India, significant in Japan, South Korea, and Russia, and sluggish in the United States and Western Europe, where current plans call for replacing, but not significantly expanding, the existing large fleets. This course of events will be the result of planned investments and government decisions, coupled with anticipated changes implemented over known horizons. Several variations on this scenario are accepted possibilities. In this paper, we first devote a brief section to the ongoing Fukushima disaster. We then revisit and discuss some of the difficulties inherent in forecasting nuclear energy supply and usage. We will also attempt to determine the reasonable boundaries of global nuclear energy supply and demand over the next fifty years based on an assessment of the most likely nuclear scenarios in major nuclear countries, as well as smaller nations. We consider the resulting range of outcomes to be the no-surprise scenario. We also examine the precursors to this range of scenarios in order to understand what occurrences could potentially change their anticipated outcomes. We then devote the remainder of our analysis to game changers.

THE NUCLEAR ACCIDENT AT FUKUSHIMA: A GAME CHANGER?

The ongoing situation at the Fukushima Daiichi Nuclear Power Station in Japan has the potential to be a game changer for nuclear energy. The events there were not included in planning horizons, yet they now could drastically affect the future of nuclear power. While the situation continues to evolve, a rough picture of the accident and its consequences has begun to emerge. An unprecedented high-magnitude earthquake, coupled with a devastating tsunami, resulted in the failure of the electrical systems that pumped in cooling water to the reactors, leading to severe overheating in both the reactor cores and spent fuel storage pools as well as the release of large amounts of radiation. The accident remains only partly controlled as of this writing (late March 2011), although progress has been made toward controlling it. The total amount of radiation release is not now known.

Predictably, opinion polls show a reduction in popular support for nuclear power, particularly in the United States and most of the European Union. However, in the United States, the political response has been muted, with both the Republican leadership and the White House expressing continued support for nuclear power. At the extreme ends, the German government announced it will accelerate the phase-out of nuclear power while, at the time of this writing, China remains committed under its new Five-Year Plan to a target of more than 11 percent of primary energy from nonfossil sources. Meeting that target requires a large expansion of nuclear power.

What will be the Medium- and Long-Term Effects?

Safety Reviews. In the immediate aftermath of the crisis, most countries that currently use nuclear power are likely to undertake major reviews of reactor safety. The U.S. Nuclear Regulatory Commission has announced an immediate ninety-day review focusing on emergency procedures, to be followed by a more extensive in-depth review of all U.S. reactors. Germany has closed seven of its seventeen reactors for safety checks. China has announced a comprehensive safety review at nuclear plants in operation and under construction. It would be surprising if other countries did not follow suit. These reviews will likely emphasize robustness against any form of loss of cooling, including loss triggered by earthquakes and tsunamis, as well as reconsidering the physical location and operation plan for backup power supplies.

The General Electric Mark 1 Reactor Design. The Fukushima reactors were the General Electric Mark 1 design; they had been in service since the 1970s. While plants of this design have operated safely for a number of decades in a number of locations, the design does not reflect the safety improvements of more recently designed reactors, particularly with regard to backup cooling systems. In fact, the design has been criticized over the years on several counts, including possible rupture of the reactor containment vessel if all cooling failed and lack of containment for the highly radioactive spent fuel rods that had been removed from the reactor core and were cooling in the water pool. Some of those concerns are accentuated by the reactor's age and the attendant material degradation. In addition, Japan's nuclear safety agency has criticized TEPCO, the owner of the reactors, for failing to carry out required inspections of equipment, including essential elements of the cooling systems. It is not clear how much this failure affected the disaster.

Thirty-two reactors of the same type as those at Fukushima are in use in several countries, including twenty-three in the United States. A number have received or are currently being considered for license extensions beyond their original planned lifetime.[3]

Spent Fuel Storage. While it is not clear at this writing how dangerous the situation inside the reactor core containment vessel remains, some of the most severe consequences of the Fukushima accident may result from a loss-of-coolant failure in the spent fuel pools. This possibility will focus attention on the storage and disposal of reactor spent fuel. There are three relevant timescales to consider: short-term storage, where spent fuel must be cooled following its removal from the reactor; medium-term storage, where spent fuel is stored in dry casks, usually on-site; and long-term disposal, which will

3. For details, see http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/fs-reactor-license-renewal.html. Other pages on the Nuclear Regulatory Commission website give the location of the units and additional relevant information.

likely require a geologic repository. Initial reviews will probably focus on the immediate hazards of cooling spent fuel once it is removed from the reactor, with special attention paid not only to protecting and containing the spent fuel that is cooling in ponds but also to large amounts of older but still radioactive spent fuel stored in casks, as is the case in the United States, where no longer-term storage or disposal has been approved. A renewed conversation about long-term storage has already begun.[4]

Where are the Effects Likely to be Felt?

More than the Usual Suspects. The accident at Fukushima will have implications worldwide, but the effects are likely to differ from country to country and region to region. Development in the United States and the European Union has been slow, with the vast majority of added nuclear capacity taking the form of license extensions and renewals. The future of nuclear power will be determined largely by the countries with the most ambitious nuclear development plans: China, India, Russia, South Korea, and to a lesser extent, Brazil, Argentina, and perhaps South Africa. This realignment of the global nuclear future is significant, possibly diminishing the influence of the traditional nuclear powers. The policies of the United States and the European Union may have less influence on the development plans of the rest of the world.

The Fukushima disaster may impact the future of nuclear power more so than either the Three Mile Island or Chernobyl accidents did. The Three Mile Island accident was contained without public health effects, while the Chernobyl accident involved a Soviet reactor of a model that was not used in the West and that lacked a crucial containment feature. The Fukushima accident, on the other hand, occurred in one of the most technologically advanced countries in the world and one with among the most nuclear experience. Furthermore, it was caused by a tsunami—a worrying aspect given that many reactors in the world, including practically all of China's reactors, are located by the sea. Moreover, it is the first nuclear disaster to occur in the Internet age, and information, rumors, and speculation have been reported to a wider audience than ever before.

What is the Future for Nuclear Power?

How will the incident in Japan change the balance between the advantages and drawbacks of nuclear power? Given the developing situation, it is too early to make accurate forecasts of its ramifications; but early indications are that the specific political and economic situations of individual countries will dominate their early and intermediate responses. We have noted the early ac-

4. Matthew L. Wald, "Japan Nuclear Crisis Revives Long U.S. Fight on Spent Fuel," *The New York Times*, March 23, 2011.

tions of Germany, China, and the United States. France, Japan, South Korea, and other countries that are highly dependent on nuclear-generated electricity have little option but to continue along the nuclear path, at least until new technologies are developed. Japan, however, is likely to be strongly affected, perhaps leading to changes in the leadership and regulation of the nuclear industry, as well as changes in such aspects as siting, reliance on seawalls, and location of backup cooling systems. Much will depend on what happens in the next few weeks. In the longer term, advanced designs that have stronger safety features, and that are less dependent on the operation of backup systems in an emergency, will see their advantage over early designs increase.

It is not possible to anticipate or prevent all accidents, but it is noteworthy that most of the serious accidents that have affected the nuclear industry were in fact *anticipated* by engineers, operators, or managers, and yet were still not prevented. This fact is specifically true of Fukushima, where Japan's nuclear safety agency had warned against siting the backup generators on low ground. The cost of prevention in most cases (with the possible exception of Chernobyl) would have been small, not only compared with the cost in dollars and political support of the most expensive accidents, but also compared with the overall cost of nuclear power. Thus, a major lesson from Fukushima and previous accidents or near-accidents concerns the management and supervision of the nuclear industry and the political and economic set of incentives involved.

Over the next few months and years, as the details of the Fukushima accident become clearer, they will affect and inform the continuing conversation about the role nuclear energy will play in the future energy mix. Undoubtedly, the competitors to nuclear power, in both the present world and a world where greenhouse gas emissions are taxed, have been at least temporarily strengthened by the event. For the longer term, while economic factors will continue to play a major role, the perceived likelihood of severe accidents will affect the political acceptability of nuclear power, particularly if it becomes clear that most such accidents can be prevented.

GAME CHANGERS: A DEFINITION

We define game changers as events that shift the future trajectory of nuclear power away from an accepted range of scenarios (the "no-surprise scenario") in a significant and lasting way. Single events, gradual but unplanned-for changes, and unexpected developments can push the future outside the horizons assumed by planners.

Game changers can certainly take the form of sudden shocks, such as a terrorist attack on a reactor, but gradual yet significant changes—incremental increases in the price of fossil fuels, for example—can also change the game. Some game changers are extremely improbable, but others (such as some form of carbon pricing) are considered possible or even likely. Events that once were universally expected to be game changers sometimes turn out not to be, while true game-changing events can be subtle and difficult to appreciate even as they occur. Thus, North Korea's withdrawal from the Nuclear Non-Proliferation Treaty (NPT) and its subsequent nuclear tests had an arguably negligible effect on the outlook for nuclear energy development. Conversely, some influential environmental organizations' shift away from opposition to nuclear power may eventually increase the acceptability of nuclear power in key countries in unanticipated ways.

Game changers would be events that spur any of the following:

- A great reduction or large increase in the relative role of nuclear energy in generating electricity worldwide;
- A great change in the role of specific countries as consumers or suppliers of nuclear power technology;
- A great change, in either direction, in the willingness of nuclear power users to adhere to existing safety and security measures and subscribe to improved ones; and
- A rise in new alliances, regional and otherwise, for the purpose of exploiting nuclear power that thereby changes some aspect of a regional balance of power.

More specifically, we consider game changers in two categories: those that may arise from developments within the area of nuclear power, broadly defined, and those motivated by changing external circumstances. In turn, we consider a number of specific areas within each category in which potential game changers may arise. Where possible, we attempt to assess the likelihood of such events and discuss their consequences for the area of nuclear power as a whole.

For the first category of game changers—those that may arise from developments within the area of nuclear power—we examine possible game changers by using the fuel cycle as an organizational framework. This category includes technological innovation anywhere in the nuclear fuel cycle, changes in subsidies, and security- and safety-related incidents at reactors. It also includes changes in the regulatory or economic environment pertaining specifically to the nuclear industry. We also discuss possible game changers for nuclear power that are not technology-related but are still specifically nuclear in character: changes in the institutions, security environment, and political considerations that could impact the future trajectory of the nuclear industry. Under this category, we also consider the effects of weapons proliferation or the discovery of illicit enrichment or reprocessing centers on the global picture for nuclear energy as well as the likelihood, severity, and probable consequences of an accident or a deliberate attack on a nuclear facility, through terrorism or war.

Within the second category of game changers—those motivated by changing external circumstances—we examine nuclear energy in a wider context. Nuclear power makes up only part of the energy mix, and factors that increase or decrease the attractiveness of one generating technology have consequences for the others. We focus in particular on the most likely game changer for the entire energy sector, including nuclear power: climate change and the possibility of a price on greenhouse gas emissions. We also explore related developments that may change the scope or composition of the electricity sector, including the implementation of a "smart grid" and the development of competitive new generating technology.

Game changers may be absent from planning horizons for many reasons. First, an event may be considered unlikely and therefore left out of planning considerations, despite lack of knowledge about its actual probability of occurrence. Second, an event may be a so-called normal accident: the culmination of several undetected failures in a complex system.[5] Unlike black swans,[6] defined as low-frequency, high-risk events, normal accidents are not low-probability and, in certain systems of high complexity, may even be considered inevitable. Finally, an event may be widely acknowledged as highly likely but be left out of planning assumptions nonetheless. This outcome may be because the consequences of the event are too unpleasant to consider, or because the short-term action required to prevent long-term damage is judged too costly.

The consequences of these game changers are often difficult to envisage. Though some are easy to foresee (a reactor accident would negatively impact the future of nuclear power, while increased subsidies from governments seeking low-emission electricity sources may improve prospects for the industry), others, such as changes in the electric grid in order to adjust to intermittent sources, have more complex consequences. Planning for game-changing events is not simply a matter of preventing unpleasant surprises or capitalizing on unanticipated opportunities; rather, it requires flexibility and adaptability. Events become game changers, and game changers become catastrophes, in part because of the inability of forecasters to anticipate and plan for them. Underlying this problem is the tendency of large organizations to make plans with the wrong mindset, selectively picking data and events that confirm what the consensus wants to believe, and to diminish the likelihood of events that do not fit that belief set. As a result, organizations—governments, utilities, and corporations—are often overly confident about the plans they decide to believe and the value of the strategies they pursue. This paper and other related work are efforts to overcome this institutionalized inertia and serve as catalysts for careful consideration of the possible effect of game changers on

5. Charles Perrow, *Normal Accidents: Living with High-Risk Technologies*, updated with a new afterword and a postscript (Princeton, N.J.: Princeton University Press, 1999).

6. Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable* (New York: Random House, 2007).

nuclear energy. Together, these efforts represent an attempt to think about nuclear issues in a different way.

With this goal in mind, our paper concludes with a brief examination of how best to deal with game changers. We discuss what strategies are available to deal with possible game changers, what strategies the major actors involved seem to be pursuing, and what research directions seem profitable for assessing possible strategies. How do we mitigate unexpected catastrophes and capitalize on opportunities? What strategies will ensure a sustainable energy future, with or without a nuclear component? What research is needed to clarify further the nature of possible game changers and the characteristics of strategies needed and feasible to deal with them?

We begin, however, with two caveats. First, it is beyond the scope of this paper—indeed, any paper—to build an exhaustive list of all the items that could have implications for the nuclear energy industry, much less to develop strategies for coping with the myriad implications. Nor is such a list necessarily useful. This paper instead seeks to examine current assumptions in context, using a few examples to expose and analyze possible flaws in the current conventional wisdom. Second, because nuclear is an emotionally and politically charged energy source, many nuclear-related events have ramifications beyond the immediate sphere of nuclear power. However, a nuclear event such as NPT breakout or clandestine proliferation is not necessarily a game changer *for nuclear energy*. This distinction is important; while we recognize that events within the nuclear arena have consequences in many areas of politics and economics, we confine our study to only those events that in our view can change the game for nuclear energy specifically.

What, then, is the utility of this approach? First, it affords the opportunity to consider the long-term effects of today's decisions. Because of long planning horizons and lifetimes of power plants, the electricity sector has a certain degree of built-in inertia. The power plants constructed and commissioned today, as well as decisions to modernize and update the power grid, will have ramifications for the entire sector for many years. It is important to take a similarly long view of the prospects for nuclear power, and a fifty-year horizon affords many opportunities for surprises. Second, considering game changers helps clarify the assumptions that define the no-surprise scenario. This exercise can help refine predictions based on a business-as-usual strategy and justify commonly held assumptions. It can also expose flaws in these assumptions or areas in which they may be incomplete. Finally, because game changers may arise in so many different areas, this approach helps improve understanding of the shifting context for nuclear energy. Considering the diversity of events that may change the game broadens the horizon for nuclear energy planners. This larger scope may help avoid some of the mistakes of the past.

The objective of this paper is to generate new insights into the future of nuclear power, and to understand how those insights may influence future policies and R&D approaches. We take no position on the desirability of nuclear power per se. Instead, our goal is to help ensure a low-emission, secure, and inexpensive future energy supply and to understand the contribution of nuclear energy to this future mix. In the course of this paper, we consider ways to mitigate potential effects adverse to this wider goal, as well as strategies to capitalize on game changers that may result in more favorable outcomes. We hope that considering game changers will prove useful for planners in the security, energy, climate, and regulatory communities as well as those in the nuclear industry.

FORECASTS

We begin by revisiting some past predictions and the assumptions underlying them. This exercise requires an understanding of forecasting in the energy sector: why, how, and to what end predictions are made, and how we evaluate their successes or failures. Forecasts serve a range of purposes. They provide a context for organizing and making sense of large data sets, help define possible future scenarios, and make clear current assumptions. Many forecasts, however, exist to further political or social agendas, and these motivations are not necessarily explicit in their construction. For example, projections of rapidly growing demand may be used to push for the construction of new power plants, while worst-case climate change scenarios may be used to spur action on emissions reduction.

The intended use of a forecast, whether explicit or hidden, shapes the process by which it is made. Many forecasting techniques have been applied to the energy sector with varying degrees of success. A simple but problematic way to predict the future is to extrapolate from present conditions; this method can yield some insight but obscures the motivating forces behind current trends. More sophisticated models may incorporate several variables, but these are sensitive to parameter choice and to assumptions about how variables interact with the wider environment. There is always, of course, the option of taking stated targets at face value. Governments and industries often make public pronouncements regarding their future plans, but these often obscure intent as well as reality. Still, these targets can help provide important insight into the motivations of policy-makers and the factors they consider most important.

Considering these forecasting methods leads to an uncomfortable truth: many past predictions have been not merely inaccurate, but spectacularly wrong. Perhaps most notorious is the 1954 prediction by Lewis Strauss, then head of the Atomic Energy Commission, that "our children will enjoy in

7. In a subsequent report by the Atomic Information Foundation, Strauss's son maintained that his father was referring to anticipated *fusion*, not fission, reactors. This distinction, if true, hardly increases the accuracy of the prediction.

their homes electrical energy too cheap to meter." Such energy was to be provided by a fleet of nuclear fission reactors that were presumably efficient, safe, and secure as well as inexpensive to license, site, and build.[7] Strauss, however, was not the only one who proved overconfident about the potential of nuclear power. The Energy Information Administration of the Department of Energy (DOE) anticipated that the United States would have 1,200 GWe[8] of installed nuclear capacity by 2000; the actual capacity was 98 GWe. The forecasts failed not only to predict the magnitude of nuclear energy but also to capture the prevailing trend. While the DOE anticipated a growth in nuclear capacity of almost 700 GWe between 1990 and 2000, in reality the industry saw a slight decline as reactors were taken out of commission.

Such problems are not limited to the nuclear industry but are found in many long-range energy models. Figure 1 shows the total U.S. energy demand in the year 2000 as predicted by several models developed in the early 1970s.[9] Notably, all the models drastically overestimate the actual 2000 figure, having failed to take into account the oil price shocks of the late 1970s and subsequent efficiency measures. They extrapolate trends from the relatively profligate late 1960s and early 1970s, when readily available cheap oil made efficiency and conservation unnecessary. Paul Craig, Ashok Gadgil, and Jonathan Koomey note that only one forecast,[10] designed to show the *possibility* of a future powered by renewables (rather than attempt a reasonable forecast from contemporary trends), comes close to approximating the actual energy consumption.

These problems remain endemic to energy forecasts. Long-term energy models that aim to track greenhouse gas emissions similarly failed to anticipate the success of shale gas drilling technologies, which have helped increase known U.S. natural gas reserves by 35 percent.[11] Because gas-fired power plants produce during combustion roughly half the greenhouse gas emissions of traditional coal-fired generation, many estimates of U.S. emissions growth have had to be revised downward. Further discoveries may lead to the widespread use of natural gas as a transition fuel, altering the picture for international climate agreements and domestic policy.

It may seem that these failures are insignificant; after all, the inability of

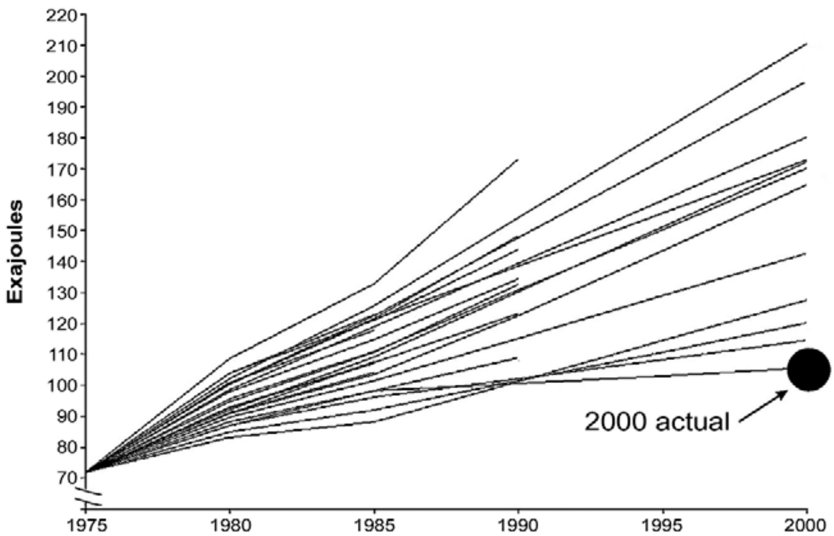
8. GWe denotes gigawatts electric, or one billion watts of electric power. This measure incorporates the efficiency of electric conversion; compare with gigawatts thermal (GWth), which measures the thermal heat produced by the power plant. A typical 1 GWe nuclear power plant produces about 3 GWth.

9. Paul P. Craig, Ashok Gadgil, and Jonathan G. Koomey, "What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States," *Annual Review of Energy and the Environment* 27 (November 2002): 83–118, http://www.annualreviews.org/doi/full/10.1146/annurev.energy.27.122001.083425.

10. Amory B. Lovins, *Soft Energy Paths: Toward a Durable Peace* (New York: Harper Colophon, 1979).

11. John B. Curtis and Scott L. Montgomery, "Recoverable Natural Gas Resource of the United States: Summary of Recent Estimates," *AAPG Bulletin* 10 (2002): 1671–1678.

Figure 1: Predicted versus Actual U.S. Primary Energy Use, 1975 to



The figure suppresses the zero baseline. Each line represents a different model used to make a prediction. Source: Paul P. Craig, Ashok Gadgil, and Jonathan G. Koomey, "What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States," *Annual Review of Energy and the Environment* 27 (November 2002): 83–118. Figure reprinted here with permission.

energy planners to foresee the oil shocks of the 1970s did not lead to catastrophic energy shortages, nor did the United States' underestimation of its natural gas reserves significantly affect national security. In both cases, the market was able to handle the unforeseen changes and devise solutions that did not lead to economic or socio-political catastrophe. The system, it seems, has proven to be relatively resilient against prediction failure. It does not follow, however, that the solutions devised were the best of all possible solutions, nor that mistakes were consequence-free. The fortunes of individual companies rise and fall with changing market conditions, and reliable predictions are important for them to increase their competitiveness under changed conditions.

Predictions are important at the state and international levels as well. Particularly when prediction mistakes involve a common good, such as environmental protection, market solutions may be inadequate to address the failure. Regulation or some form of externality pricing may be required and can be imposed only by governments or outside bodies. Trusting market solutions to materialize in the absence of reliable predictions means governments may be ill-prepared to provide for the common good of their citizens. Additionally, preparation may be a question of scale: terrorist attacks, accidents, or proliferation concerns are best dealt with at the state or international level, not at the vendor or utility level. Accurate predictions, or at least a thorough understanding of their limitations, are therefore crucially important, for both the players that must compete in a changing market and the governments and international institutions that must prepare for a changing world.

The question remains, why do forecasts so often fail to anticipate future events? It may be that they are simply wrong; their initial assumptions may give an inaccurate or incomplete picture of the present. Physical or economic processes may be poorly understood or modeled so that even correct inputs lead to incorrect conclusions. More often than not, however, models fail because they do not anticipate events outside these initial assumptions: they do not consider game changers. In this paper, we focus on this latter category of events as applied to future projections for nuclear power. This requires us both to explain what we believe to be the current state of forecasting for nuclear energy over the next fifty years and to make clear the scope of the assumptions and initial conditions that enter into these predictions. We call this assumed reference case the "no-surprise scenario."

NO-SURPRISE SCENARIO

The expression "no-surprise scenario" is, at some level, inaccurate: most decisions, economic and political, are made under uncertain conditions and with the knowledge that such uncertainty exists. Thus, in many cases (and where possible), uncertainties are hedged. The no-surprise scenario is not a single scenario, but a set of boundaries on what is considered reasonable and to be planned for. Below, we describe what might be considered the generally accepted view of the course of future events, the view that underlies, for instance, the assumptions of national and international government agencies, utilities, and vendors.

The present is an unusually uncertain time for nuclear power for two main reasons. The first relates to economics. To a varying extent, the developed countries in North America and Europe that use or are considering using nuclear power are facing high unemployment along with high public debt. There is little agreement among those countries about how to face these difficulties: their responses involve different mixtures of economic stimulus, austerity measures, and other policy tools. Moreover, there is no assurance that changes in government will not affect those responses.

The second uncertain factor is government action on climate change. If governments at the city, state, or national level impose some form of a price on greenhouse gas emissions, this development will affect the future of nuclear power and that of the other means of providing energy; similarly, "green" subsidies will make some investments more attractive and others less. As of this writing, a climate bill remains stalled in the U.S. Senate, presumed dead. Other major greenhouse gas emitters lack coherent and effective plans to reduce emissions, and despite progress at the Cancun Climate Summit in Winter 2010, no strong international consensus has yet emerged.

Those two uncertainties are already reflected in different ways in some national plans for investing in nuclear energy: for example, China has accelerated its nuclear plans, while the United States has slowed its nuclear development. These differences point to the challenges inherent in defining a single *global* nuclear future. The current state of the nuclear industry is somewhat fragmented, depending strongly on local political and economic conditions. Most energy forecasts rely on a complicated array of economic, social, environmental, and political factors. Assessing the place of nuclear energy in the future mix brings with it an additional set of complications. Waste, reactor accidents, proliferation and security threats, and changes in public perception are dealt with differently in different regions. A serious accident, while unlikely to bring about a lasting shutdown of the 20 percent of electricity generated by nuclear in the United States, let alone the higher numbers in France, Japan, and South Korea, could prevent or seriously delay expansion. Conversely, accidents are unlikely to impose more than a temporary delay in the plans of China, India, and Russia, where public opinion is not as determinative and the need for electric power growth is greater than in developed countries. A continuing or deepening recession could induce a major downward trend globally by reducing both demand and financing. However, because different regions have weathered the recession with varying degrees of success, the post-financial crisis landscape for nuclear power will likely be regional in character.

However, it is not impossible to talk sensibly about a no-surprise scenario on a global scale. The rapid development of communications technology would surprise even the most prescient observers of the 1970s, and business, politics, and social activism have globalized in ways once unimaginable. The economic, political, and technological aspects of nuclear power have components that do not respect national boundaries. It is therefore useful to consider a global picture, albeit one constructed as a sum of disparate parts from scenarios at the national and regional levels. This piecewise approach can help differentiate those factors that affect nuclear power within the country or region from those that are likely to transcend boundaries. In the following sections, we build the global scenario from its regional components, focusing not on specific projections but on the current conditions that create assumptions used in building models. We do not dispute that other forecasts consider different scenarios, and these may indeed turn out to reflect future reality more accurately than the scenarios discussed below. After all, nearly everything is predicted by someone. In defining the no-surprise scenario, we are not interested in predicting the future with any degree of accuracy, but in collecting the conventional wisdom with respect to the nuclear sector in the regions we consider.

The United States

While the recession slowed investment plans, the medium-term situation in the United States appears relatively favorable to nuclear power. Although the outcome of specific U.S. DOE loan guarantee reviews is uncertain, the DOE has available, as of January 2011, $10.2 billion in guarantee authority.[12] The timescale for new reactors could continue to be delayed depending on politics and the length of the current economic downturn: consider, for instance, that demand for electricity in the United States has gone down in the past three years. If the increases in energy demand projected earlier are realized,[13] the no-surprise scenario foresees nuclear power persisting at roughly 20 percent of U.S. electric generation. This scenario assumes that the current nuclear generating capacity is extended[14] and that currently planned new coal- and gas-fueled generators come online in approximately the current proportions. The United States generates about 30 percent of the world's nuclear power; given current plans, this share is expected to decrease.

The U.S. situation at the front and back ends of the nuclear fuel cycle is also changing. While the United States was the world's largest nuclear exporter in the early decades of the nuclear age, there is no longer a purely U.S.-owned nuclear reactor exporting company, though there are extensive commercial agreements: for example, between Toshiba, the majority owner of the former U.S. reactor builder Westinghouse, and the Shaw Group, a U.S. engineering and construction firm.[15] The United States continues to be active in other areas of the international nuclear market, including with respect to nuclear fuel. AREVA, URENCO, and the U.S. Enrichment Corporation are either building or planning to build new enrichment facilities in the United States. At the back end of the fuel cycle, there is at present no approved final disposal method for civilian nuclear spent fuel in the United States. Yucca Mountain has been closed, and a Blue Ribbon Commission on America's Nu-

12. *Nuclear News*, January 2011, 24. This number is slated to increase, but by how much is uncertain in the present U.S. fiscal climate.

13. Stephen Ansolabehere, John Deutch, Michael Driscoll, Paul E. Gray, John P. Holdren, Paul L. Joskow, Richard K. Lester, Ernest J. Moniz, and Neil E. Todreas, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, Mass.: Massachusetts Institute of Technology, 2003).

14. Currently, of the one hundred nuclear power reactors in the United States, sixty have received license renewal extensions into the 2030s and 2040s, and twenty-six more license extensions are under review or expected; see *Nuclear News*, January 2011, 28.

15. See ibid., 24, for a description of such an arrangement. We note that architectural and engineering services are fundamentally different from reactor development, design, and construction and do not require the same degree of advanced technology.

16. See the statement from Secretary of Energy Steven Chu from January 29, 2010, http://www.energy.gov/news/8584.htm.

clear Future has been appointed to provide recommendations for developing a safe, long-term solution to manage the nation's used nuclear fuel and nuclear waste.[16]

A game changer would be an event or trend that either entirely shuts down new nuclear plans or drastically increases the role of nuclear in the U.S. energy mix. For either outcome to materialize, new investments in the tens of billions of dollars over and above what is now planned, whether in alternative generation if nuclear power were to be shut down or in additional nuclear generation if it were to be increased, would have to be made. These investments would be required of the utilities and industry, the universities that educate the kinds of engineers needed, and, directly or indirectly, the government. At present, such excursions are not part of the no-surprise scenario. Rather the U.S. "game" is to extend the lifetime of current reactors as much as possible and, if loan guarantees hold up, to build a few new ones.

Despite current administration and congressional support, and aside from concerns about slowed demand, the domestic U.S. market regarding nuclear power is characterized by extreme caution: nuclear power, as one longtime observer has remarked, is nobody's favorite—or at least no politician's or investor's favorite. Growing concerns about climate change have led influential environmental campaigners to reluctantly support nuclear energy. Secretary of Energy Steven Chu, representing the Obama administration's view and that of a significant group in Congress, has repeatedly said a clean energy standard could include clean coal and nuclear along with renewables.[17] Nevertheless, the future of nuclear power remains vulnerable to a serious safety or security incident, particularly if it affects any new facility.

Europe

The European nuclear landscape is as diverse as Europe itself. The proportion of electricity generated by nuclear power ranges from none in Austria, Denmark, Greece, Ireland, Portugal, and Norway to more than 80 percent in France and close to 100 percent in some small Eastern European countries. The political and economic situations, as well as popular attitudes to nuclear power, differ widely among EU member states. This diversity means that there is no single European no-surprise scenario. However, as with the global scenario, we can construct a picture of the expected European nuclear future as the sum of disparate parts. In the short term, investment and licensing activities indicate that the role of nuclear power is poised to remain roughly

17. See, for example, The Huffington Post's report on Secretary Chu's recent testimony before Congress, http://www.huffingtonpost.com/2010/12/07/steven-chu-clean-energy-s_n_793382.html. See also the reports on the bipartisan Millennium Energy Summit held December 7, 2010: for example, http://www.nucleartownhall.com/blog/tag/new-millenium-nuclear-energy-summit/.

constant over the next few decades. In those countries that currently utilize nuclear power, there are no immediate plans for substantially increasing the rate of investment. Countries may, of course, change their future energy policies by eliminating or adopting nuclear power: Germany, Sweden, and Italy have recently reversed course. However, the overall European scenario is unlikely to change by any large percentage.

Several European states have long been major nuclear exporters. France is a large exporter mainly through the AREVA Corporation; Germany and the United Kingdom also participate in exports on their own and via URENCO, a British-Dutch-German jointly owned enrichment facility that provides about a quarter of enrichment services in the world.

Nuclear power provides about a third of total electricity for the European Union, amounting to nearly 30 percent of the world's nuclear power. Under the no-surprise scenario, this world share is expected to decline. As with the United States, upward departures from this scenario are not now considered likely. The vulnerability of the nuclear power industry to serious incidents varies by country. The same uncertainties that affect the United States—concerns about the length of the current recession, its impact on demand, and the lack of global policy agreement regarding climate change—also affect many European states.

Japan

Japan has increased its nuclear power generation, opening eight new plants last year. The contribution of nuclear to total power production is about 30 percent, constituting about 9 percent of total nuclear power generated worldwide. Japan has a complete fuel cycle facility and supporting technology. Japan's nuclear exports are carried out mainly through two major Japanese-Western owned companies, the General Electric-Hitachi and Toshiba-Westinghouse combines. The country has very recently decided to support nuclear exports more actively than in the past, in particular to India, Vietnam, and, controversially, Middle Eastern countries.

The 30 percent domestic share of total power is slated to increase to 40 percent under present plans. These plans are likely to be carried out in part because the cost of nuclear power is expected to decline in Japan relative to hydrocarbon-fueled power, and in part because an increased competition for those hydrocarbons from developing countries will heighten the strategic value of nuclear electricity. Those factors have in the past overridden shorter-term economic concerns—nuclear investments continued at reduced levels through the long Japanese economic slowdown—and they are likely to continue to do so in the future. In view of the Fukushima accident, however, any prediction about the Japanese nuclear future is more than usually uncertain at this time.

South Korea

Nuclear power provides about 40 percent of South Korea's electricity, amounting to roughly 6 percent of world nuclear electricity production. This share is slated to increase to 60 percent of South Korea's electricity generation under the no-surprise scenario. Like Japan, South Korea has a strong nuclear infrastructure and track record, and this projection appears reasonably well assured. Many of the same economic and strategic arguments that apply to Japan also apply to South Korea. There has been little serious political opposition to the program in the last thirty years, and such opposition as exists has been caused by seeming incompetence or carelessness, not by fundamentals. A major factor in South Korea's plans is positioning the country to become a leader in exporting nuclear technology; to this end, South Korea recently won an order to build four reactors in the United Arab Emirates. South Korea has also shown a strong interest in acquiring enrichment and/or reprocessing facilities. It is currently negotiating on this subject with the United States, whose permission is needed under existing arrangements. South Korea has been less affected by the current economic downturn than most of its fellow advanced economies.

India

India currently has nineteen nuclear power plants (two of which began commercial operation in 2010) and more than 3 GWe of nuclear capacity under construction. As part of a major development push involving the entire energy sector, India plans nearly to double this nuclear capacity in the next twenty years. Under present plans, this increase will comprise indigenously developed pressurized heavy water reactors; light water reactors from France, Russia, and other suppliers; advanced heavy water reactors based on the thorium cycle; and fast breeder reactors, the first of which is anticipated to come online in 2012. Therefore, the official scenario for India is one of rapid development, but there is considerable uncertainty regarding these ambitious plans. Given four different reactor technologies, a new fuel cycle based on thorium, and an R&D and industrial infrastructure still being developed, many view these government plans as an upper limit for the expansion of the nuclear sector in India. If the plans are realized, India would produce more than 1 percent of the world's nuclear electricity. India has also continued to grow during the current recession and is increasingly participating in the international nuclear market. The Fukushima disaster has raised India's concerns about regulatory effectiveness and tsunamis in particular and may result in reform of the regulatory structure.

China

China's nuclear power plans are both larger in scope and more assured, based on past performance, than India's plans. The 12th Five-Year Plan anticipates growth from the present 13 GWe to about 40 GWe (from eleven to twenty-five plants) by 2015,[18] and plans thereafter are much more ambitious.[19] Financing and approval exist for at least the initial stages of this growth, and the necessary infrastructure is developing and keeping pace with the construction.

Nuclear expansion is part of both a move away from the dominance of coal and an emphasis on strategic industries, which include new energy technologies such as nuclear power, as well as contributing industries such as materials R&D. Nevertheless, the pace of development has raised flags of caution, not least from the State Council Research Office (SCRO), which makes independent policy recommendations to the State Council on strategic matters. "Going too fast could threaten the long-term healthy development of nuclear power," the SCRO has said.[20] The SCRO also noted that introducing a safety culture takes longer than technical training, that China has fewer nuclear regulators per reactor than other countries, and that regulators in China are less well paid than others in the industry.[21] In partial response, some Chinese organizations, notably the Guangdong Nuclear Power Corporation, are extending and standardizing the training of nuclear reactor operators.

Because of the ambitious scope of China's plans (China's 2030 target of 200 GWe is about half the world's total nuclear power capacity today), the size of its current effort, and the relative newness of its nuclear industry, it is difficult to call any projection in China's case a no-surprise scenario: the government scenario itself is surprising, yet no particular deviation from it is any more probable. The scenario represents an upper limit on what could be accomplished. If that ambitious upper limit is approached, China would become the most important global actor in the nuclear power sector.

Russia

Russia now generates about 16 percent of its electricity from nuclear power

18. "China's 12th Five-Year Plan: How It Actually Works and What's in Store for the Next Five Years," a report from APCO Worldwide, December 10, 2010, 6–7, http://www.apcoworldwide.com/content/PDFs/Chinas_12th_Five-Year_Plan.pdf. The 12th Five-Year Plan guidelines were published in September 2010, and the plan is slated to come into force in March 2011.

19. According to the World Nuclear Association, "China has 12 nuclear power reactors in operation, 24 under construction, and more about to start construction soon. Additional reactors are planned, including some of the world's most advanced, to give more than a tenfold increase in nuclear capacity to 80 GWe by 2020, 200 GWe by 2030, and 400 GWe by 2050. China is rapidly becoming self-sufficient in reactor design and construction, as well as other aspects of the fuel cycle"; see "Nuclear Power in China," on the website of the World Nuclear Association, http://www.world-nuclear.org.

20. "Maintain Nuclear Perspective, China Told," *World Nuclear News*, January 11, 2011.

21. See the summary at http://www.world-nuclear.org/info/inf63.html.

and plans to increase that share to 25 percent in the next two decades, a goal that would require doubling the existing number of reactors. While timescales are uncertain, Russia's past record, along with the existing infrastructure and financing, makes it likely that those plans will be realized, although perhaps not on the officially declared schedule. If they are, Russia will produce around 10 percent of the world's nuclear power, a share that will probably decrease in light of India's and China's plans.

Russia has a full fuel cycle facility and has been a strong international civilian nuclear supplier. A recent memorandum of understanding between Siemens, the German high-technology industrial supplier, and Rosatom, the state corporation controlling nuclear activities in Russia, could presage a stronger entry into that field.

The Rest of the World

More than 90 percent of the world's nuclear power is generated in the countries listed above, with the United States, the European Union, and Japan alone accounting for 70 percent of the total. If nuclear energy begins to appear attractive and feasible for many other countries, this picture of dominance could change. Developing countries that have expressed interest in nuclear power include Algeria, Cameroon, Chile, Egypt, Georgia, Ghana, Indonesia, Iran, Jordan, Kenya, Malaysia, Mexico, Mongolia, Morocco, Namibia, Nigeria, the United Arab Emirates, and Vietnam. While these countries are often ignored in discussions of the global nuclear future, the expansion of nuclear power to the developing world has the potential to change drastically the debate surrounding nuclear issues.

It is difficult to make detailed predictions about such a diverse group of countries, but the energy sectors in many developing countries have certain aspects in common. Access to reliable electricity is limited, particularly in rural and impoverished areas. Important sources of energy include hydropower and biomass, both of which have deleterious environmental impacts. Finally, the transmission and distribution infrastructure is weak compared to that in more developed countries, leading to losses of 15 to 30 percent compared with 7 percent reported in OECD countries. These differences mean that efficiency and conservation measures are highly cost-effective investments in developing countries, while at the same time, an ever-increasing demand not present in the West requires the constant introduction of new capacity. Additionally, financial constraints may favor solutions that are inexpensive in the short term even though they may not make the most economic sense in the long term. Given the high up-front cost of nuclear power and often limited grid capacity, the no-surprise scenario vis-à-vis nuclear energy in the developing world will likely involve increased discussion and expressions of interest, with relatively few serious building commitments.

Technology transfer agreements, efficiency improvements, and indigenously developed solutions will all play a part in the future energy mix of the developing world. Nuclear energy may enter the picture for reasons of political prestige or competition, cooperation agreements with regional powers, or a desire to add value to domestic uranium or thorium resources. It may become more attractive if lower-cost suppliers with few political demands enter the market, or by suppliers that offer "cradle to grave" nuclear power programs, thus relieving their customers from concerns over acquiring fresh fuel and disposing of spent fuel. Developing countries that wish to adopt nuclear power could also look to regional leaders for guidance, assistance, or examples of how to develop a program. The nuclear sectors in South America and Africa are dominated by Brazil and Argentina, in the former, and South Africa, in the latter. The decisions of these regional leaders could have ramifications for the energy policies of their regions. It is fair to say that the no-surprise scenario for the developing world is prone to more variations than that in the developed world.

The Global Picture

These regional scenarios, some aspects of which are summarized in Table 1, can be used to assemble a global no-surprise scenario. This projection, based on current investments and the political and economic factors that underlie them, is one of growth by tens of reactors in India, China, and South Korea over the next twenty or thirty years, slower growth in Japan, and replacement, alongside some growth, in the United States and the European Union. However, we note that given the large nuclear power fleet in the United States and EU countries, the replacement market there over the next several decades could be quite large.

The resulting nuclear picture is one of reawakening from the nearly dormant situation of recent decades, with many new reactors and increased interest in different designs. This should not, however, be confused with the vaunted "nuclear renaissance" predicted by enthusiastic observers. Other sources of electric power generation are slated to grow in tandem with the increase in nuclear (or in the case of renewables, perhaps more quickly). While nuclear generation will increase, the share of total electricity generated by nuclear is not likely, in the no-surprise scenario, to change significantly. In particular, the spectacular growth of nuclear capacity in China must be seen in the context of rapid overall development. Even if China were to attain its mid-century nuclear energy goal, its total electric generating capacity would also grow. As a result, nuclear will be a much larger fraction of the total than the present 1 to 2 percent and coal would come down from roughly 75 percent to 50 percent of the total, which is approximately the present fraction in the United States.

In order to construct an accurate picture of the world landscape, it is important to understand how changes in one region affect others. How do trends catch on? How do technological innovations spread, and how are they

Table 1: Generation of Nuclear Electricity, in Terawatt-Hours (TWh), by State or Group of States, in 2009

Entity	TWh Generated (2009)	No-Surprise Scenario	Remarks
United States	800	Replacement, some growth	No disposal policy
European Union	850	Replacement, some growth	Some states changing policies
Japan	240	Increase from 30% to 40%	
South Korea	140	Increase from 40% to 60%	Major export program envisaged
China	~70	Rapid rate of increase	Triple in 10 to 20 years, export program
India	~13	Rapid but less sure rate of increase	Double in 20 to 30 years
Russia	150	May increase to 50%	Timescale uncertain
Rest of the World	~350	Uncertain, varied	

Source: Table compiled by the authors based on data from various public sources, including the U.S. Energy Information Administration, the International Energy Agency, the International Atomic Energy Agency, and the World Nuclear Association. This table represents the pre-Fukushima no-surprise scenario. Changes to date have been marginal, but more changes may be on the way.

adapted for different purposes? What are the effects of policy changes in one country for its neighbors and for the world as a whole? A piecewise approach can emphasize regional trends, but it fails to capture the connections among countries in a globalized world. In searching for game changers, we hope to examine how localized events may propagate and the effects they may have on the global nuclear future. Studying game-changing effects may lead to a positive feedback loop, in which analysis of the event may lead to a more integrated picture of the no-surprise scenario, which may in turn refine the assumptions creating that scenario.

GAME CHANGERS FROM NUCLEAR TECHNOLOGY

We begin by examining the possible advances in nuclear science and technology that could alter the future of nuclear power. The nuclear fuel cycle—mining, enrichment, reactor operation, and reprocessing, storage, or disposal—provides a convenient organizing framework for this discussion. A full discussion of the intri-

22. For example, David Bodansky, *Nuclear Energy: Principles, Practices, and Prospects* (New York: Springer-Verlag, 2004).

cacies of the fuel cycle is beyond the scope of this paper, and interested readers can consult one of the many excellent existing reviews.[22]

Mining and Milling

The first steps in the nuclear fuel cycle are the mining and milling of natural uranium. The most obvious potential game changer at this stage is a shortage of recoverable natural uranium, but we do not deem this a likely eventuality. Should current resources prove uneconomical, new extraction technologies or even fuel cycles may be implemented. However, since fuel extraction and fabrication costs represent a negligible contribution to the overall economics of nuclear power, it is difficult to see a game changer at this stage.

Is the current worldwide nuclear energy capacity sustainable? Are current resources sufficient to fuel increased global demand for nuclear power? To operate a 1 GW reactor for one year, about 170 tons of natural uranium are needed, assuming a once-through cycle and thermal efficiency of around one-third. The total world usage is around 65 kilotons per year. The amount of uranium mined annually accounts for only two-thirds of this world nuclear demand, with the shortfall made up by reenriched depleted tails, repurposed military uranium, and reprocessed nuclear fuel. Figure 2 shows the geographical distribution of known recoverable resources according to the report *Uranium 2009* (the Red Book).[23]

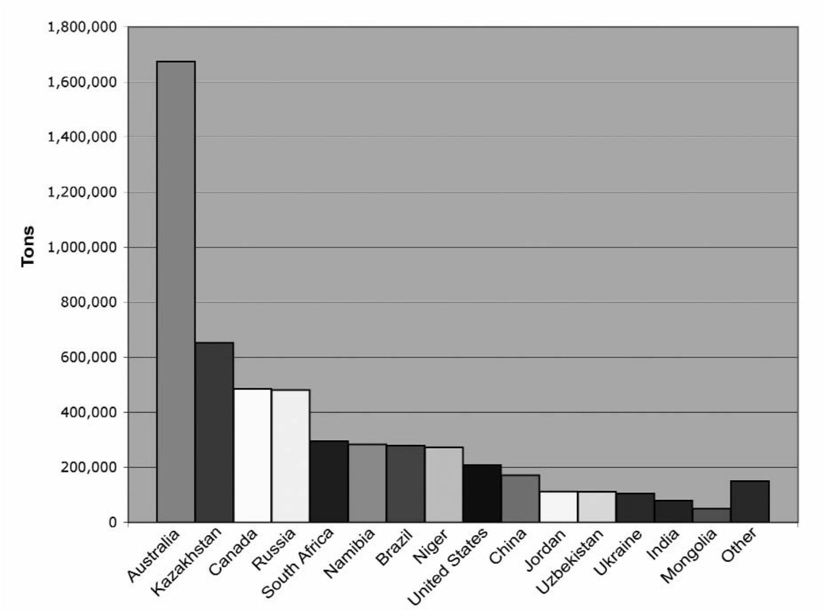
The figure does not take into account the ore grade, which ranges from 20 percent in certain deposits in Canada to less than two-millionths of a percent in sedimentary rock. Energy costs to extract reasonably pure uranium increase with decreasing grade. However, the use of even very low-grade ore does not significantly increase the cost of nuclear power per kilowatt-hour, which is relatively insensitive to the price of natural uranium. In fact, fuel costs for nuclear power are proportionally lower than for other major energy sources, as shown in Table 2.

The raw material for nuclear power is not a renewable resource, and concerns have been raised[24] that future exploration may yield deposits that are uneconomical to extract or are sufficiently low-grade to require an unacceptable investment of energy to separate pure uranium. However, we view this eventuality as rather unlikely: if uranium is scarce, there will be more incentive to look for it. Deposits that have thus far been uneconomical to extract may become attractive in a high-demand future. In addition, the arguments in Jan

23. *Uranium 2009: Resources, Production, and Demand* (Nuclear Energy Agency/Organisation for Economic Co-operation and Development, 2011).

24. See, for example, Jan Willem Storm van Leeuwen and Philip Smith, *Nuclear Power: The Energy Balance* (Chaam, The Netherlands: Ceedata Consultancy, 2008); and Michael Dittmar, *The Future of Nuclear Energy: Facts and Fiction*, chap. III: "How (un)reliable are the Red Book Uranium Resource Data?" (2009), available through Cornell University Library's open-access e-prints, arXiv:0909.1421v1.

Figure 2: Known Recoverable Resources of Uranium, in Tons, as of 2009



Source: Figure created by authors based on data from *Uranium 2009: Resources, Production, and Demand* (Nuclear Energy Agency/Organisation for Economic Co-operation and Development, 2011).

Table 2: Total Levelized Cost and Variable Operation and Maintenance (O&M) Cost (Principally Fuel Cost) for Electricity Generating Technologies Brought Online in 2016, by Cost per Megawatt-Hour (MWh)

Plant Type	Total Levelized Cost ($/MWh)	Variable O&M including Fuel
Coal (conventional to advanced with carbon capture and sequestration)	100–130	24–26
Gas (Combined Cycle)	80	55
Advanced Nuclear	119	9
Wind	150–190	0
Solar Photovoltaic	400	0
Solar Thermal	250	0
Geothermal	116	0
Biomass	111	25
Hydro	120	7

Figures have been rounded. Source: Energy Information Administration, "Levelized Cost of New Generation Resources in *Annual Energy Outlook 2011*," http://www.eia.doe.gov/oiaf/aeo/electricity_generation.html.

van Leeuwen and Philip Smith rely on the assumption that all high-grade deposits have already been identified and exploited and that all subsequent deposits will be extremely low-grade; recent discoveries of high-grade ore in Canada cast doubt on the accuracy of this assumption. A 2003 MIT study[25] found that known recoverable resources of uranium appear to be sufficient to support a modest increase in nuclear construction over the next century; we agree with this analysis and do not see a natural resource shortage as a likely game changer.

Projections of uranium availability consider global resources, yet in the real nuclear market, national boundaries matter, as do such international commitments as the obligations of state-parties to the NPT and those undertaken by members of the Nuclear Suppliers Group (NSG). For reasons of energy security, countries may not wish to rely on imported uranium. India in particular was denied access to the international uranium market until very recently and has very little indigenous natural uranium. It does, however, have large deposits of thorium, which can be used to breed fissile U-233 isotopes. Because thorium is fairly abundant worldwide, if India succeeds in both developing and exporting this technology, it could effectively remove both its own resource constraints and uranium availability in general from the nuclear energy equation. Now that India has access to the international uranium ore market it is uncertain to what extent it will make the investments needed to use thorium technologies.

There is also the possibility of developing alternatives in extracting uranium from seawater. Seawater contains about three parts per billion of uranium. While this is a tiny concentration, the sheer volume of the oceans means that up to 4 billion tons of uranium may be extracted from seawater, enough to sustain ten times current consumption for more than six thousand years. While this method is not used commercially at present, a Japanese team has succeeded at extracting uranium from seawater at about three times the cost of mining. This method could prove attractive to countries without indigenous uranium resources, and if it can be done with minimal environmental impact, it could be a viable alternative to mining. Still, economical extraction from seawater is likely to be a game changer only in the limited area of uranium resource exploitation. It is unlikely to change the game for nuclear power as a whole.

Enrichment

Because enrichment is a complex process and poses an inherent proliferation danger, game changers in the enrichment stage of the nuclear fuel cycle are possible in many dimensions. On the technical side, new enrichment processes may be game changers not because they are easy to conceal, as conventional wisdom holds, but because they may be implementable on small

25. Craig, Gadgil, and Koomey, "What Can History Teach Us?"

scales. On the economic side, the entry of new suppliers into the enrichment market could change the game, as could a concerted geopolitical effort to manage the proliferation risk posed by the technology.

In order to discuss game changers for enrichment, it helps to understand the current state of both technology and the market. Very few reactors run on natural uranium; after mining and milling, most nuclear power plants must then undertake enrichment to increase the concentration of the fissile isotope U-235 relative to the naturally abundant isotope U-238. In the previous section, we showed that the economics of nuclear power are relatively insensitive to the costs of raw uranium; likewise, the enrichment process adds relatively little to the cost per kilowatt-hour. At present, enrichment services are provided to the international market by a few dominant players. France, the United States, and Russia, along with URENCO, are the major international providers of enrichment services. In addition, a number of other countries have (or have had) enrichment facilities for domestic purposes; more have either indicated their interest in acquiring this capability or are in the process of acquiring it. Current world enrichment capacity exceeds current world demand, making for a competitive market, albeit one heavily constrained by suppliers' agreements. While the vast majority of power reactors use low enriched (near or below 5 percent) uranium, which cannot be used directly for nuclear weapons, once a country acquires the capability to enrich to this level it is comparatively simple to achieve the high enrichment required for weapons-grade uranium. Enough highly enriched (at or exceeding 90 percent) uranium for a nuclear weapons requires only a small percentage of the separative work needed to provide fuel for a standard power reactor for a year. Thus, enrichment facilities are considered sensitive from the standpoint of nuclear proliferation.

Currently, a large proportion (two-thirds and growing) of enrichment is accomplished by cascades of centrifuges, which separate isotopes by means of the centrifugal force. Global Laser Enrichment, a joint venture of General Electric, Hitachi, and Cameco, has recently met with some initial success in an enrichment plant that would rely on the separation of isotopes by selective laser excitation of the electrons of isotopes, a process known as SILEX. If a laser enrichment plant is successfully developed to full scale, this method could provide cheaper and, in some ways, less technically demanding enrichment services than the currently dominant centrifuge-based enrichment plants. Some argue that this process, unlike large centrifuge projects, can be more easily concealed and therefore poses a new proliferation threat. However, clandestine enrichment is not necessarily a game changer per se. Technologies that are easy to hide already exist: Iraq's clandestine enrichment program, for example, involved a calutron mass spectrometer, one of the oldest enrichment technologies in existence. In order to constitute a true game changer from the standpoint of proliferation, a new enrichment technology must be not only concealable but also smaller in scale and simpler to implement. Current enrichment technologies are available only on large scales; therefore, proliferation requires active involvement at the state level. It is not clear whether SILEX would lead to changes in this respect. An enrichment process that makes enrichment available to sub-state actors, potentially posing unacceptable terrorism risks, could have a profound impact on how nuclear power is regulated and exported in the future.

Even without a new technology, if some current trends continue, the nuclear fuel enrichment market could look very different in a few years than it does now. At least two such trends are evident. One is the attempt by countries rich in uranium ore, such as Australia, Mongolia, and Kazakhstan, to add value to their uranium exports by building the conversion and enrichment facilities needed to export enriched nuclear fuel. The other is the reactivating or upgrading of enrichment facilities outside the major exporting countries. For instance, Argentina, Brazil, India, Iran, Pakistan, South Africa, and South Korea all are either reactivating facilities, upgrading ongoing facilities, experimenting with separation technologies, or negotiating the necessary agreements to enable them to start an enrichment process. None of these countries, except perhaps South Africa and eventually South Korea, is likely to be able to compete on price with existing large-scale suppliers of enrichment services in the short or medium term, but the efforts may continue for strategic and developmental reasons. Moreover, the loss of the present oligopoly could make the enforcement of nuclear exports guidelines difficult or irrelevant or, alternatively, lead to more multinational, perhaps regional, facilities. The latter course is more desirable from the standpoint of inhibiting proliferation and terrorism, but it requires the states involved to accept some internationally agreed constraints. Such acceptance will hinge on a variety of local circumstances, but in our view, one factor is likely to be generally important: the international agreement must retain the competitiveness that characterizes the present enrichment market, where the United States, URENCO, France, and Russia are competing, with China and others as possible suppliers in the future.

A number of proposals have been put forward to lessen the risk associated with the spread of enrichment technology.[26] The proposals range from internationalization or further multinationalization of the facilities to a freeze

26. Such proposals include those made by the Bush administration, "President Announces New Measures to Counter the Threat of WMD," a fact sheet issued by the White House, February 11, 2004, http://www.whitehouse.gov/news/releases/2004/02/20040211-4.html; by Mohammed ElBaradei when he was Director General of the International Atomic Energy Agency, published as "Towards a Safer World," *The Economist*, October 16, 2003, http://www.nuclearfiles.org/menu/key-issues/nuclear-weapons/issues/proliferation/fuel-cycle/elbaradei-economist.htm; and by several authors, including Chaim Braun and Michael May, "An International Regime of Fresh Fuel Supply and Spent Fuel Disposal," *The Nonproliferation Review* 13 (1) (March 2006). In particular, see the recent review by Pierre Goldschmidt, "Multilateral Nuclear Fuel Supply Guarantees & Spent Fuel Management: What are the Priorities?" *Daedalus* 139 (1) (Winter 2010): 7–19.

on the number of states that have such facilities. Little agreement has been reached. States have been reluctant to give up their ability either to buy enrichment services in a competitive market or to overcome any present or future opposition to their fueling nuclear reactors. Acceptance will therefore depend on both economic and political dimensions of any proposal. On the economic side, clients of multinational or regional facilities must be satisfied that they could not buy enrichment services more inexpensively or otherwise on better economic terms elsewhere. By the same token, the international agreement must not constitute a barrier to entry for other, potentially more competitive suppliers or for new technologies. On the political side, clients must be satisfied that their political relations with the sponsors of some facilities will not interfere with their ability to purchase enrichment services from other facilities, assuming that the constraints related to preventing proliferation or terrorism are met in all cases. In other words, disputes on grounds having nothing to do with the utilization of nuclear energy, such as those concerning commercial arrangements, territory, or human rights, must not result in curtailed access to enrichment facilities.

Some of the solutions presented to date (freezing the number of states that can provide enrichment services or relying on a single international authority) do not meet these minimum criteria, but there is no a priori reason why other solutions could not meet them.

Reactors

For nuclear reactors, meaningful game changers stemming from technological developments would address three main problems: high initial costs, generation of spent fuel that contains plutonium, and high radiotoxicity of waste products.

Again, it is useful to review the current state of reactor technology and economics. Most nuclear power reactors in the world today are variations on a single basic design, the light water cooled and moderated reactor (LWR). LWRs use low enriched uranium (LEU, typically 4 to 5 percent U-235). With LEU, it is impossible to sustain the chain reaction that leads to a nuclear explosion: weapons require highly enriched uranium (HEU), with concentrations up to and exceeding 90 percent U-235.

These current power reactors have a thermal efficiency around 33 percent and a capacity factor ranging up to and a little more than 90 percent when operated in base-load mode. They have excellent safety records, in part because the greatest risk to workers and the public comes from mining and transportation and also because even the worst accident for this type of reactor (the Three Mile Island accident in the United States in 1979) did not lead to any significant off-site damage to people and property. Nuclear power can be competitive with other means of generating electricity, depending on the cost of capital, the length of time for licensing and construction, and factors having to do with competing technologies. Nuclear reactors emit less than a tenth of the greenhouse gases emitted by coal-fired generators of the same size, including emissions during construction, mining, transportation, operation, and shutdown; they emit little or no other pollutants. The radioactivity emitted throughout the nuclear fuel cycle in particular, including operations, is less than what is released from coal mining operations and coal combustion.

Further improvements in efficiency and safety, as well as work toward additional lifetime extensions, are either ongoing or planned; these incremental developments lie well within planning horizons and cannot be considered game changers. Greater efficiency requires materials that can withstand more radiation and higher temperature, allowing the nuclear fuel to stay in a reactor longer and burn a higher fraction of its fuel and leading to fewer interruptions for refueling. Higher temperatures would increase the ratio of electric power to heat loss. The key to improved safety (besides better operator training and regulatory compliance, which are not technical but are the main contributors to safety) lies with more "passive" safety devices, ones that activate when needed without human or electrical intervention.

In the past, the expansion of nuclear power has been accompanied by real and imagined proliferation threats. Plutonium in spent fuel, while not ideal for weapons, can in theory be separated and used to build a bomb. Some of the ideas currently considered by reactor builders and governments would reduce but not eliminate these fuel diversion concerns. Others would change the nature of the current fuel cycle, either by relying more on plutonium separation for their fuel or by using thorium, which involves a different fuel cycle. These technological changes give rise to political and security challenges, which we consider in the next section. The impact of very advanced concepts that have been studied only on paper or with computer modeling, such as the traveling wave reactor, is difficult to envisage; however, it is unlikely that even spectacular new designs will lead to nuclear dominance in the electricity sector globally unless these designs changed what are seen as the downside factors for nuclear power: namely, the high front-end investment cost, the generation and disposal of radioactive materials, and popular perceptions of its safety and security.

Small modular reactors (SMRs) could alleviate the first of these problems but only at a cost and for much smaller applications than nuclear power plants' current designs allow. Models close to commercial availability range from 45 to 125 MWe, and they cost far less than standard-size reactors, are more adaptable to less capable grids and lower demand sites, do not require as many scarce specialized vendors, and require fewer refuelings during their lifetimes. On the other hand, a number of regulatory issues remain to be settled, SMRs cost more on a dollar-per-megawatt basis than larger reactors, and the first models would pose the usual "first of a kind" issues. These reactors may also displace smaller-capacity renewables or pose increased security and transportation problems, as spent fuel must be stored at or transported to more locations. Perhaps the biggest drawback of SMRs is the increased potential for accidents: while technology is modular and exportable, safety culture seldom is. These challenges notwithstanding, three utilities have so far committed to getting one such unit approved for commercial use in the United States.

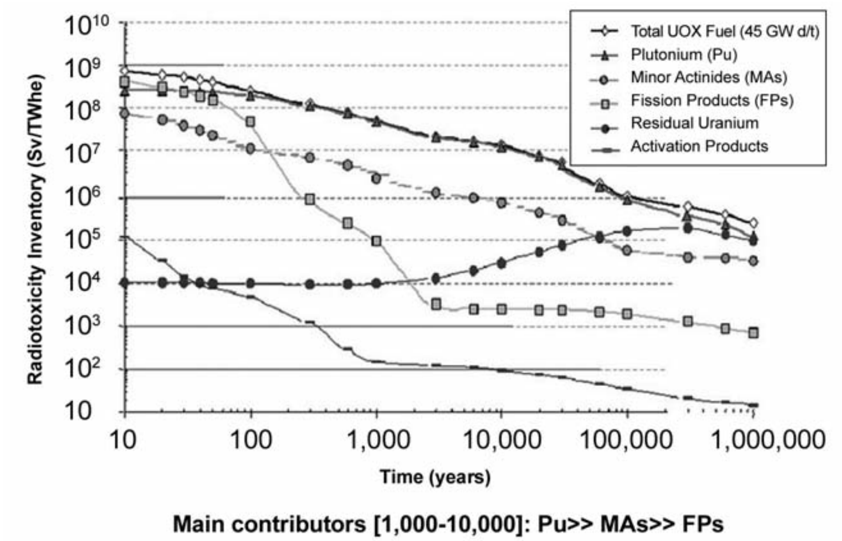
On a much longer timescale, several advanced designs that would alleviate at least one of the problems listed above are under investigation. These designs include new versions of ideas abandoned when LWRs were first commercialized, such as sodium-cooled or lead-bismuth cooled reactors with extended fuel cycles, gas-cooled reactors, pebble-bed fuel reactors, and thorium-based reactors, as well as new ideas, including the traveling wave reactor (TWR). This design, if realized, promises to extend fuel life to forty to sixty years with no enrichment (other than an initial fuel load) or reprocessing, and to run on depleted uranium. A commercial version of the TWR would likely require further research into new materials capable of withstanding high temperatures and neutron fluence.

Inexpensive, viable, and sustained nuclear fusion, should it become reality, would drastically change the game for nuclear power. There are two main approaches to sustained fusion: magnetic confinement, in which the fusion plasma is held in place by a magnetic field, and inertial confinement, in which a fuel target is heated and compressed until light elements can fuse. Both approaches are the subject of large-scale scientific investigations. The International Thermonuclear Experimental Reactor (ITER) facility in Cadarache, France, utilizes magnetic confinement and is scheduled to come online in the 2020s. The Lawrence Livermore National Laboratory in California investigates laser fusion at its National Ignition Facility (NIF), and there are other smaller efforts elsewhere in that direction. Some of the underlying physics has now been tested, notably in the case of magnetic confinement, and the NIF may be a year or two away from igniting a small amount of nuclear fuel. But in both cases, important scientific and materials questions remain outstanding. Commercial fusion power of either type, even in a best-case scenario, is probably decades away. If successful, however, this technology would do away with waste and proliferation issues as we know them. Viable, economical fusion would likely be a game changer, not just for nuclear fission but for the entire energy sector.

The Back End of the Fuel Cycle

The back end of the fuel cycle is perhaps the most politically contentious problem in nuclear energy. Spent fuel is comprised of about 95 percent un-

Figure 3: Radiotoxicity Inventory, in Sievert per Terawatt-Hour (Sv/TWhe), in Spent Nuclear Fuel at Ten Years and Beyond



Source: Charles Madic et al., "Futuristic Back-End of the Nuclear Fuel Cycle with the Partitioning of Minor Actinides," *Journal of Alloys and Compounds* 444–445 (2007): 23–27. Figure reprinted here with permission from Elsevier Ltd.

burned natural uranium, which is not particularly radioactive and could be handled safely. However, a further 4 percent is composed of fission fragments, most of which remain dangerously radioactive for nearly five hundred years. The remaining fraction consists of very heavy elements, including plutonium, that have been created along with the fission process and the U-235 that has not been fissioned. These elements, along with certain fission products, constitute high-level waste and will remain highly radioactive for hundreds of thousands of years. Figure 3 shows how the radiotoxicity of spent fuel elements changes over time. (To provide some context: a few sievert over the human body will cause severe radiation disease or death.) In 2009, U.S. nuclear plants generated about 0.7 terawatt-years.

At present, there are two methods for handling this spent fuel. One, strongly advocated and expensively pursued by the United States, is the so-called once-through cycle: after the first pass through the reactor, spent fuel is not reused for its remaining energy content but, after a cooling period of years, is sent to an underground depository and buried irreversibly. Several other countries, notably Finland and Sweden, are also pursuing this method. The U.S. policy is now in limbo as a result of the Obama administration's 2009 decision to abandon the chosen repository site of Yucca Mountain in Nevada, after some twenty years and $20 billion of investigation and investment. This was arguably a purely political decision, and it is not inconceivable that it may be reversed. In the meantime, spent fuel is stored in sealed casks at utility sites after an initial cooling period of several years.

A variation on this approach has been adopted by Russia, which is accepting spent fuel and other high-level waste from other countries for long-term storage and possible disposal. Russia, along with France, anticipates that spent fuel may acquire commercial value in the future.

The other approach, once pioneered in the United States but now used in France, Russia, Japan, and some other countries,[27] is to reuse or recycle the spent fuel in order to utilize its plutonium content. Most American observers, unlike their French and Russian counterparts, consider this method to be more expensive than the once-through method, given present prices of uranium. The comparison is complicated for a number of reasons, including different sunk costs and different economic assumptions. Furthermore, the comparison is not perfect because separating the plutonium and other actinides makes the remaining waste smaller in volume and less radioactive after some time.

Two factors increase the urgency of the spent fuel debate. First, because of local political opposition, most countries find it difficult to site spent fuel depositories. As a result, nuclear exporter countries or firms that could offer "cradle to grave" programs, whereby the importing country would buy, in one package, the reactor, fueling services for its lifetime, and disposal of spent fuel outside the country, are likely to have an advantage in selling reactors and fuel services. This issue is discussed further in a subsequent section on the changing nuclear market. The other factor stems from the possible utility of the plutonium in spent fuel for weapons. As noted in an earlier footnote, this "reactor-grade plutonium" is usually not well suited to weapons use because of its high radioactivity, but weaponization is theoretically possible. Expansion of nuclear power may therefore constitute a diversion danger for countries or groups that have access to a plutonium separation plant.

Technological game changers at the back end of the nuclear fuel cycle could therefore include new recycling methods that do not separate the plutonium in spent fuel from its radioactive matrix, reducing the chance it could be diverted to weapons use. While such innovations in reprocessing have been considered in the past, none have been commercialized, and it is likely that they would require new fuel and reactor designs as well. The most likely game changers at the back end include new models of viable storage and disposal or technology that helps facilitate cradle-to-grave packages. These developments, while they may be aided by new technology, are perhaps more a function of the political and market forces we discuss later.

Accidents

The potential of accidents to alter the no-surprise scenario depends on many

27. See http://www.world-nuclear.org/info/inf69.html for a list of countries as of 2008. China is claiming it also can and will reprocess nuclear fuel.

factors: the developmental stage at which they occur, their consequences, and the public perception of nuclear power at the time they occur. Early accidents, mainly in developmental facilities, did not affect the growth of nuclear power, which at the time was popularly supported. The Three Mile Island accident, which caused no casualties, and Chernobyl, which did, had large political impact. However, these accidents came at a time when the growth of nuclear power had ceased in both the United States and Russia. Therefore, they caused little change in *actual* planned investments, although they had a devastating impact on the anticipated future role of nuclear power in the United States and Europe.

Things can go wrong at any stage of the nuclear fuel cycle. Mines, enrichment plants, reactors, separation plants, and storage and disposal sites are all vulnerable to accidents of varying degrees of severity. The term *accident* is used in the industry for a wide variety of events, ranging from some that affect only a single facility to some that may result in serious damage to the population, environment, or economy. The accidents most likely to change the nuclear game are those that are both severe and peculiarly “nuclear”: that is, those arising not in the mining or transportation categories, but rather at reactors, at the storage sites used in the early years after spent nuclear fuel is removed from the reactors, or at recycling plants.

Nuclear power plants are complex technological systems of interacting parts that also require interactions with human operators. Such complex systems are subject to what Perrow (cited above) calls “normal accidents”: the culmination of interlinked technical failures compounded by human error. These incidents, while impossible to predict and difficult to prevent, are not low-probability outliers: they are dangers inherent in complex technology. Accidents must therefore be expected over the fifty-year time horizon of this study. They have certainly occurred over the past sixty years, although the accident rate and consequent damage to health and environment have been lower for nuclear energy than for hydrocarbon generation. The accidents were almost always due to human error compounded by the complexity of the technology.

Accidents can have societal, financial, and environmental and health consequences. Significant environmental and health consequences have been extremely rare after the early days with the important exception of Chernobyl, which involved a reactor design that would not have met Western safety criteria. Societal consequences have been more frequent, as exemplified by the 1979 Three Mile Island accident, which focused attention on reactor operator training and compounded a growing sense of disenchantment with nuclear power in the United States. Lesser accidents elsewhere in the United States and the world have also had a negative impact on the general perception of

28. See the table, “Nine Nuclear Power Plant Accidents with More than US$300 Million in Property Damage, to 2010,” at http://en.wikipedia.org/wiki/Nuclear_power.

nuclear power, which is still seen as a dangerous unknown by the media and much of the public. The financial consequences of both actual accidents and serious infractions of governmental safety rules have been severe. The Three Mile Island accident is estimated to have cost its operator well over $2 billion, and several other accidents have cost their operators over $1 billion.[28] Even a near-accident, such as erosion in a core component discovered, in 2002, at First Energy's Davis-Besse plant in Ohio, can cost an operator over $600 million.[29] The financial costs of accidents and infractions make potential investors wary, but their impact on plans for the future depends heavily on the economic and political environments in which they occur.

While technological advances and improvements in regulation and training have made a major difference, it is prudent and realistic to expect accidents and to develop contingency plans to minimize their consequences. A principal concern in this regard is the possible expansion of nuclear power to new users and new exporters. The most significant way to minimize accidents and to alleviate their consequences if they occur is to adopt a safety culture at every step required in the construction and operation of nuclear facilities. Safety can be a hard sell to new users: it is an added cost and often a factor in slowing operations. Delivery of a certified design unit to an approved site is only the first step: regulators must maintain a presence in-country, personnel must be trained to report problems to regulators (and be protected when they do so), and management must be trained to deal with problems openly. The International Atomic Energy Agency (IAEA) can play a crucial role, especially at the time of expansion to new users, yet it has not received the additional budget and political support it needs.[30]

Former chairman of the U.S. Nuclear Regulatory Commission, Richard Meserve, notes that the present international safety regime is an ad hoc mixture of intergovernmental organizations (of which the IAEA is the most prominent), several multinational networks, and stakeholders in the international nuclear industry held together by "a framework of international conventions, international safety standards, codes of conduct, joint projects, and international conferences and workshops."[31] Licensing and operational standards for individual projects remain under national authority. Meserve rejects the idea of an international regulator that would displace national authorities, but he proposes a number of steps to improve the existing regime, including

29. See http://www.ohio.com/business/87712397.html.

30. For an authoritative review of this issue, see the report from the Commission of Eminent Persons, chaired by Ernesto Zedillo and commissioned by the IAEA, *Reinforcing the Global Nuclear Order for Peace and Prosperity: The Role of the IAEA to 2020 and Beyond*. The report recommends that IAEA members should allocate the organization "considerably larger resources"; see http://www.iaea.org/newscenter/news/2008/2020report.html.

31. Richard A. Meserve, "The International Global Nuclear Safety Regime," *Daedalus* 138 (4) (Fall 2009): 102ff.

strengthening international safety and security services, broadening communication networks for sharing operational practices and incident information, and improving harmonization and international evaluation of designs and practices. Implementing such recommendations becomes increasingly important as the number of new entrants to nuclear power grows.

The nuclear industry throughout the world is vulnerable to accidents, including those impacting health and the environment. Changes such as those advocated by Meserve, together with a well-cultivated safety culture, will help minimize both the frequency and severity of accidents and mitigate their consequences when they occur. An accident of even moderate severity, coupled with a political culture of ambivalence or nervousness regarding nuclear power, represents a serious potential game changer.

GAME CHANGERS FROM NUCLEAR POLITICS AND ECONOMICS

In this section, we consider developments that do not concern technology yet are specifically "nuclear" in character. Any consideration of nuclear energy requires attention to the complex political and economic issues that surround this unique energy source. Here, we look at possible game changers from the changing nuclear market, from acts of terrorism or war, and from nuclear weapons proliferation.

The Changing Nuclear Market

New customers and new suppliers have the potential to change the game for the nuclear market. America's and other Western states' domination of the nuclear supplier market, and their attendant influence over accepted norms of behavior, is waning. This development has ramifications for future international agreements that may shape the nuclear market. In particular, rules designed to minimize nuclear weapons proliferation may be less important to the new entrants into the market than they are to the United States, with its far-flung military commitments. There is at present no clear indication whether this is the future direction or not.

The nuclear power market has been international almost from its inception, but the roles of individual states and the rules under which they operate are changing. In particular, the United States, while retaining major roles in nuclear fuel and components, now only supplies reactors through foreign companies (Westinghouse is part of Toshiba) or combines (the General Electric-Hitachi group). Russia, which as the Soviet Union was long a supplier to its allies and, since the early 1970s, to India, is now the largest reactor exporter in the world, followed by France. South Korea has successfully begun a program of reactor exports, as has China. Both, but especially China with its low-cost structure, have considerable growth potential. Japan, with a large and advanced domestic industry, is becoming an exporter of reactors as well.

On the whole, the rules for nuclear exports have gradually been tightened, with the list of items considered sensitive expanding and the powers given to the IAEA increasing. Some of this tightening occurred as a result of India's using an imported Canadian reactor to make weapons-grade plutonium, culminating in a nuclear test in 1974. Much more tightening occurred following the discovery of the full extent of Iraq's nuclear weapon program after the 1991 Gulf War. At the same time, starting at least two decades ago, a parallel supply system for technology and materials relevant to nuclear weapons was developed, led by Pakistan's principal scientist, A. Q. Khan. It is not entirely clear to what extent that system has been shut down.

A major and perhaps prophetic departure from this gradual tightening of exports controls occurred in 2006, when the United States and India agreed to a framework for an agreement that would legitimize nuclear trade between the two countries. Heretofore, NSG members had not engaged in such trade with India because India is not a party to the NPT and has a nuclear weapon program. Indeed, India's first nuclear explosion in 1974 spurred the formation of the NSG. The U.S.-India agreement has cleared most legislative hurdles in both countries and most operational details have been worked out. As a result of it, the other NSG members have agreed to an exemption for India. These agreements remain controversial, as they depart from the prior behavior of NPT parties toward non-parties that have acquired nuclear weapons, as all four non-parties have.

Who will be the major players in the nuclear market in the future, who will set the rules, and will any game changer arise from the shifts in importance among market participants? The factors most likely to affect this issue are cost, government financial backing, and assurance of nuclear fuel services for both the front and back ends of the fuel cycle.

Cost. Both initial and levelized cost[32] matter. In a strictly competitive world, with long-term financing available, levelized cost would be the sole determinant of market winners. However, with governments often both guaranteeing the initial investment and subsidizing the cost of electricity to customers, initial cost affects the choice of supplier. For some new-entrant buyers with limited budgets, initial cost may be determinative. Thus, if nuclear power expands to new countries, low initial cost suppliers such as Russia and, in the future, China are likely to do particularly well.

Government Backing. In all countries, major nuclear power investments made by private firms are backed by various forms of government financial guarantee. This is not specific to nuclear power: infrastructure investments,

32. The levelized cost of electricity is the constant (that is, level) cost of a kilowatt- or megawatt-hour of electricity sufficient, over the lifetime of the electrical generating plant (nuclear or not), to repay the cost of the investment in the plant including interest plus its operating cost (fuel, operations, and maintenance).

for which benefits flow in part to society as a whole rather than just to paying customers, usually require some form of government support. The role of government support is particularly prominent in the case of nuclear power investments, which are large and suffer from political as well as economic uncertainty. Rising exporters Russia, South Korea, and France all benefit from export-support policies on the part of their governments. Purely U.S. exporters went out of business when the domestic market for new reactors ended; it is an open question whether new ones will arise.

Fuel Services. Domestic enrichment, when not motivated by a desire for nuclear weapons, has been motivated by a perceived need for energy security and, in the case of reprocessing, for reasons of waste management. Most buyers of nuclear power plants have neither of those motivations and little taste for investing resources into, and fighting battles over the siting of, high-technology enrichment plants, which, unlike reactors, generate no electricity or income. For these buyers, assurance of fuel supplies for the lifetime of the plant and provisions to take back and dispose of spent fuel affect their choice of supplier. The French firm AREVA comes close to offering a complete range of services. A former executive there characterized their offering as "cradle to funeral home" rather than "cradle to grave" because France does not yet have a disposal site ready. The Russian firm Rosatom, benefiting from a Russian law that permits acceptance of other countries' spent fuel, can offer the full range.

These economic factors are likely to be the primary determinants of future nuclear purchasing decisions. Political decisions and norms can constrain those decisions. Therefore, a major question is whether future buyers and sellers will view international arrangements aimed at security or safety as economic. The answer to that question will determine the future of those arrangements.

Terrorism and War

Terrorists[33] could carry out nuclear attacks in a number of ways, each of which would have different consequences for nuclear power. The most likely scenario is an attack with radioactive material in an area unrelated to nuclear power. Such a "dirty bomb" attack could increase the general public fear of all things nuclear, making it more difficult to construct nuclear power facilities in some countries. However, an attack of this form would very probably be viewed as an intelligence, law enforcement, and public health issue, not as an issue directly relevant to nuclear power. At the other end of the relevance scale would be an attack on a nuclear reactor that succeeded in releasing a

33. We are indebted to Professor Martha Crenshaw of Stanford University and Dr. Michael Levi of the Council on Foreign Relations for enlightening presentations and discussions of these issues.

significant amount of radioactive material. This latter kind of attack might well stop nuclear power programs, at least temporarily, and the resulting augmented security would likely increase the cost of nuclear power, thereby making it less attractive compared to other investments. Somewhere on this scale would be an attack by a terrorist or a state using a nuclear weapon that would destroy either a nuclear reactor, spewing its radioactivity over the surrounding area, or a city. The consequences of this last kind of attack would reach far beyond the nuclear power area; nuclear power would be only one of many areas drastically changed.

The different modes of attack would pose different degrees of difficulty to a terrorist group. Medical and industrial isotopes, some of which are highly radioactive, are widely distributed and less difficult to acquire than either weapons materials or spent civilian nuclear fuel. Fashioning them into a bomb or some other irradiation device without too much risk to the handlers poses some difficulty, but a sophisticated group could overcome it. Such a device would destroy and contaminate a building and a limited distance beyond it (a block or less for most feasible devices) but would also cause high cleanup costs and perhaps some panic. The effect on life, health, and environment beyond the building targeted would be minimal.

A successful attack on a modern power reactor—that is, one that would breach the containment building and spread radioactivity—poses great difficulty, even with access to inside personnel and/or to aircraft. However, it would be the most direct way in which terrorism could affect the future of nuclear power. Some spent-fuel storage facilities are not as well protected as reactors and could pose a greater risk, but attack on them would still not be easy and would require a sophisticated, well-trained, and equipped group. It is well to recall that any terrorist group intending to carry out an attack on a nuclear facility or with a nuclear weapon would face a number of obstacles, each independent of the other: securing appropriate equipment and materials, enlisting appropriate personnel, ensuring enough time and space to train, obtaining financing, crossing national boundaries, possibly with contraband equipment, and so on. While none of these obstacles is impossible to overcome, the chances of overcoming them all in succession could be quite small.

To be sure, terrorist use of some nuclear tool would not surprise intelligence or law-enforcement agencies, which have considered and have worked to prevent such attacks for decades. Al Qaeda planners discussed attacks on a nuclear reactor with airplanes, and there have been attempts to acquire nuclear materials. Affiliated groups and others have attempted radioactive attacks without success. Terrorist groups, Al Qaeda in particular, have an innovative and adaptive approach; should the opportunity to execute a nuclear attack present itself, it is likely they will capitalize on it.

The consequences of nuclear terrorism would vary with the location of the attack, the group that perpetrated it, the damage to life and property, and when directed at nuclear power infrastructure, the degree of attachment to and support for nuclear power by the government where an attack occurs. For some governments, nuclear facilities are symbols of government power and national progress—which can have the effect of enhancing their value as terrorist targets. For countries where nuclear facilities are simply a part of the electricity supply, other targets that are more symbolic, easier to attack, and that would involve larger numbers of potential casualties may be more attractive.

Theft of nuclear material remains a terrorist threat. As Matthew Bunn notes, "Theft of potential nuclear bomb materials is not just a hypothetical worry; it is an ongoing reality, highlighting the inadequacy of the nuclear security measures in place today: the . . . IAEA has documented some 18 cases of theft or loss of plutonium or HEU confirmed by the states concerned (and there are more cases that the relevant states have so far been unwilling to confirm, despite the conviction of some of the participants)."[34] None of those cases involved enough material to make an explosive, but, as Bunn notes, the full story is not known and the existence of criminal networks devoted to this pursuit is clear. Again, as with safety, the problem has been addressed by what Bunn calls "a patchwork quilt of programs and initiatives" largely led by the United States. Among these are the U.S. Nunn-Lugar Cooperative Threat Reduction program, a multibillion dollar, multiyear government effort; the UN Security Council resolution 1540, requiring all states to pass and enforce legislation making it a crime to help nonstate actors acquire materials for weapons of mass destruction; and the more recent U.S.-Russia led Global Initiative to Combat Nuclear Terrorism. However, the main thrust of the efforts is carried by national intelligence and law-enforcement agencies, which vary widely in quality, priorities, and degree of cooperation with each other. The IAEA performs an essential role here again by tracking reported incidents and sponsoring relevant research for detection, but it is not a preventive organization beyond that. UN resolution 1540 and similar counterterrorist international resolutions lack effective implementation mechanisms. Because this area is so deeply enmeshed with sometimes conflicting national priorities and intelligence methods, it is more difficult to obtain international cooperation in implementation than is the case for safety. Terrorism thus remains a potential game changer, one which, many agree, has very negative consequences but around which international cooperation remains difficult.

Given the relative absence of pertinent data, terrorism is the least amenable area to any informed speculation about possible game changers for nuclear power. Perhaps the only assured prediction is that the consequences of terrorist use of some nuclear tool would depend crucially on the location and circumstances of the attack.

Nuclear Proliferation

34. Matthew Bunn, "Reducing the Greatest Risks of Nuclear Theft and Terrorism," *Daedalus* 138 (4) (Fall 2009): 112.

The links between the growth and spread of nuclear power, on the one hand, and the development of nuclear weapons, on the other, are complex. While nuclear power and nuclear weapons involve different technologies, some of the underlying physics and some of the underlying technical training and instrumentation (for instance, in dealing with radiation) are common to the two fields. Furthermore, plutonium, one of two nuclear weapons materials, is made in nuclear reactors, albeit reactors that are much smaller and usually of a different design than those used for nuclear power. The other nuclear weapon material, uranium that has been enriched to 90 percent or more of the isotope U-235, is made in much the same enrichment facilities as are used for providing nuclear reactors with LEU. To make matters more difficult, the enrichment capability needed to fuel a power reactor of the most common size is much greater than what is needed to make one weapon's worth of HEU.

Yet nuclear weapons proliferation has not significantly affected the global picture for nuclear energy. The historical record shows that, while the U.S. Atoms for Peace program was correlated with the worldwide growth in nuclear power that ended with the Chernobyl accident, proliferation events were not correlated with changes in nuclear power growth. Neither China's, India's, or North Korea's nuclear test seemed to affect the trajectory of nuclear power in the world, whether nuclear power was growing at the time or not. There were probably several reasons for this lack of correlation. The motivations for a nuclear power program and for a nuclear weapons program are not the same, and for at least one nation that considered then abandoned its nuclear weapon program, they were in fact contradictory.[35] The plutonium made in most power reactors is contaminated with highly radioactive isotopes of plutonium, making it hard to design into and handle in nuclear weapons. The enrichment capacity for a few weapons is far less than that needed to supply power reactors on an economic scale. All known cases of nuclear weapon proliferation made use of materials from facilities dedicated entirely or nearly fully to that purpose.[36] Furthermore, nuclear power plants are expensive com-

35. In an April 2, 2008, address at a dinner to mark the fiftieth anniversary of the International Institute for Strategic Studies (IISS), Carl Bildt, a former Prime Minister of Sweden, spoke of Sweden's experience from a half-century ago: "[I]t was when civilian requirements for cheap and reliable electricity came to dominate Swedish nuclear programs . . . that the military option became much more complicated and expensive"; reprinted in *Perspectives on International Security*, Adelphi Paper 400–401 (London: IISS, 2008), 32.

36. India is an exception, having used its Canadian-built, supposedly civilian research reactor (for which the United States had provided heavy water) to make plutonium, including the material used for its first nuclear explosion in 1974.

37. The U.S. Nuclear Non-Proliferation Act of 1978 Section 104d permits peaceful nuclear exports to non-nuclear-weapon states "only if such states accept IAEA safeguards on all their peaceful nuclear activities, do not manufacture or otherwise acquire any nuclear explosive device, do not establish any new enrichment or reprocessing facilities under their de facto or de jure control, and place any such existing facilities under effective international auspices and inspection."

pared to the facilities needed for nuclear weapons materials, and being tied into an electric grid, the economic cost of diversion is high and the probability of discovery higher than for a dedicated covert facility.

Safeguards against the use of civilian nuclear facilities were strengthened by the entry into force of the NPT (1970); the U.S. Non-Proliferation Act of 1978,[37] which was motivated by India's diversion; and similar regulations adopted by the other members of the NSG. The great majority of states have found it in their interest to adhere to the NPT. The United States, working with its NSG partners, has been a leader in preventing sales of sensitive nuclear technologies outside the agreed NPT and NSG guidelines. It has often been successful, particularly so in the past two decades, after those guidelines became more complete and clearer partly in response to Pakistan's, Iraq's, North Korea's, and Iran's activities. The list of sensitive nuclear exports gradually expanded as did IAEA inspection powers, especially in the wake of the first Iraq war. These expanded powers are mainly included in the so-called Additional Protocol (AP). States agree to the AP voluntarily, but the United States has declared that it will limit nuclear exports to states that sign it and has promulgated that policy for other nuclear exporters, with partial success. So far as is known, no diversion of nuclear materials has occurred from safeguarded plants.

The success, though, has been partial. Certain state-parties to the NPT have developed weapons programs. Safeguards and implementing agreements did not prevent Iraq's effort, North Korea's nuclear explosions, the A. Q. Khan network, or Iran's current efforts. Iran poses a particular challenge, not only because of its threat to destroy another country, but also because much of the international community, led by the United States and its allies, is trying to prevent Iran from acquiring sensitive enrichment facilities that Brazil, for instance, was allowed to acquire and that South Korea may soon be allowed to acquire. Iran has hidden much of its activities from IAEA inspection, in contravention of its obligations; however, for a number of states, that argument is not as persuasive as it is to the United States and its allies. As these states enter the nuclear market or become bigger players in it, the influence of the United States and its traditional allies may become weaker at the same time that demand for those sensitive facilities increases in some quarters because of perceived insecurity. That could certainly affect the safeguards and other conditions under which the nuclear export market operates and might well be a game changer for nuclear power.

A recent analysis by Scott Sagan and Steven Miller[38] brings up other reasons to be concerned about the future spread of nuclear power. For one, the

38. Scott D. Sagan and Steven E. Miller, "Nuclear Power without Nuclear Proliferation?" *Daedalus* 138 (4) (Fall 2009): 7–18.

39. Ibid., 11.

Table 3: Existing and Aspiring Nuclear Power States

Americas	Western Europe	Eastern Europe	Central and South Asia	East Asia/ Oceania	Middle East	Africa
Existing Nuclear Power States Argentina Brazil Canada United States Mexico	**Existing Nuclear Power States** Belgium Finland France Germany Netherlands Spain Sweden Switzerland United Kingdom	**Existing Nuclear Power States** Armenia Bulgaria Czech Republic Hungary Lithuania Romania Russia Slovakia Slovenia Ukraine	**Existing Nuclear Power States** India Pakistan	**Existing Nuclear Power States** China Japan Korea	**Existing Nuclear Power States** Iran	**Existing Nuclear Power States** South Africa
Aspiring Nuclear Power States Bolivia Chile Dominican Republic El Salvador Haiti Jamaica Peru Uruguay Venezuela		**Aspiring Nuclear Power States** Belarus Croatia Estonia Greece Latvia Poland	**Aspiring Nuclear Power States** Bangladesh Georgia Kazakhstan Mongolia Sri Lanka	**Aspiring Nuclear Power States** Indonesia Malaysia Myanmar Philippines Singapore Thailand Vietnam	**Aspiring Nuclear Power States** Bahrain Egypt Israel Jordan Kuwait Oman Qatar Saudi Arabia Syria Turkey UAE Yemen	**Aspiring Nuclear Power States** Algeria Ghana Kenya Libya Morocco Namibia Nigeria Senegal Sudan Tanzania Tunisia

Table taken from Scott D. Sagan and Steven E. Miller, "Nuclear Power without Nuclear Proliferation?" *Daedalus* 138 (4) (Fall 2009): 10. Sources: IAEA Power Reactor Information System, http://www.iaea.org/programmes/a2; Frank N. von Hippel, ed., "The Uncertain Future of Fission Power," review draft, http://www.fissilematerials.org; Polity IV Project, *Political Regime Characteristics and Transitions, 1800–2007*, http://www.systemicpeace.org/inscr/inscr.htm. Figure © Scott D. Sagan; used here with permission.

safe and secure operation of nuclear power facilities requires "good governance," which is lacking among some of the aspiring nuclear power states (see Table 3). Second, "each known or strongly suspected case of a government starting a secret nuclear weapons program, while it was a member of the NPT and thus violating its Article II NPT commitment, was undertaken by a non-democratic government."[39] Figure 2 in Sagan and Miller's essay shows that aspiring nuclear power states have significantly lower democracy scores than present nuclear power states, according to the World Bank's World Governance Indicators.

GAME CHANGERS FROM OUTSIDE THE NUCLEAR FIELD

Nuclear energy makes up only part of the electricity mix, and factors that increase or decrease the attractiveness of one generating technology have consequences for the others. Thus, we should consider nuclear energy in context:

as one choice among several for the electric sector.

The one policy development most likely to be a game changer for the electricity sector, and therefore nuclear energy, is policy action designed to mitigate the threat of global climate change. This action, whether in the form of subsidies, a carbon tax, or a cap-and-trade program, has the potential to drastically change the economics of energy use and generation. Here, we consider the possible effects such policies may have on nuclear power. We also consider two related game changers: the role of nuclear energy in a new "smart grid" and the potential rise of new technologies that could displace or compete with nuclear in a future energy mix.

Climate Change as a Game Changer

The threat of climate change has the potential to reshape the entire electricity sector. While the exact consequences of a rise in global temperatures remain the subject of debate and research, the basic science is clear: carbon dioxide is a greenhouse gas, and it is emitted in large quantities by the burning of fossil fuels. Since the Industrial Revolution, human generated greenhouse gas emissions have contributed to an increase in global surface temperatures. Many scientists believe that increasing the atmospheric concentration of carbon dioxide significantly higher than its preindustrial level of 260 to 280 parts per million by volume (ppmv) will lead to irreversible climate change. The current concentration stands at 390 ppmv and rising, presenting an urgent need to develop and implement low-emission sources of energy, particularly electric-ity, which uses a large and growing share of total primary energy. (Hereafter, *emissions* refers to the emission of greenhouse gases.)

This has significant ramifications for the nuclear energy industry. In the course of generating electricity, nuclear power plants emit no carbon dioxide, the primary greenhouse gas produced by humans, and the nuclear industry may benefit from policies designed to curb emissions growth. However, climate policy will not by itself lead to such a resurgence, and the role of nuclear power will depend on the form, strength, and implementation details of emissions-control mechanisms. Thus, aggressively moving forward on climate change can be seen as a necessary but not a sufficient condition for a large increase in nuclear power's share of the worldwide electricity market.

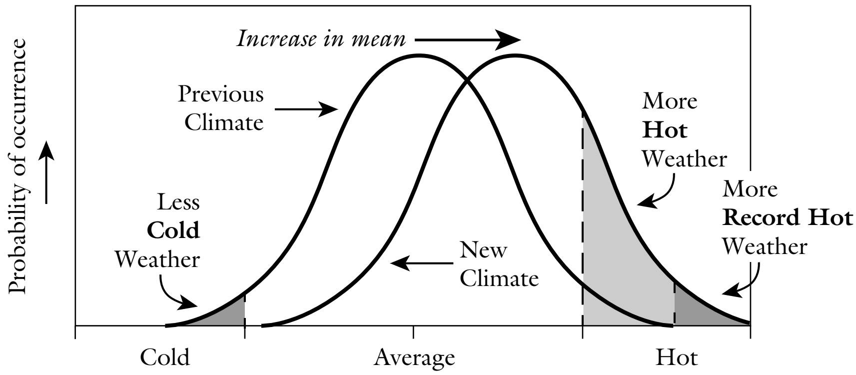
The private sector is beginning to exhibit some interest in low-carbon technologies, such as nuclear energy, but only government action can change the incentive structure to make these technologies competitive with fossil fuels on a ten- to twenty-year timescale. The role of nuclear power in an emissions-constrained world will depend on several factors. First, an expansion of nuclear power is likely contingent on its efficacy in reducing emissions in a timely way, as compared to competing technologies. On the one hand, nuclear power is a tested and generally cost-competitive technology that generates no emissions during operation, while renewable technologies are not yet cost-competitive and have been tested only on relatively small scales. On the other hand, if financing, political, and safety concerns delay the construction of large-scale nuclear power plants, it may be preferable to rely on other technologies to make the necessary emissions cuts. Second, the role of nuclear power depends on its *perceived* efficacy in reducing emissions. The changing views of investors and the public toward nuclear power will help determine the willingness of utilities to construct expensive nuclear plants and of campaigners and regulators to include nuclear as a "green" technology. Third, prospects for nuclear power will depend heavily on the form of regulation adopted. How emissions controls are implemented will affect all players in the electricity sector, including nuclear power. A patchwork of differing local or state-level regulations is likely to produce different consequences from strong federal legislation, whether dictated by national policy, such as the now-defunct Waxman-Markey bill would have provided, or imposed in compliance with an international agreement. Additionally, the form such controls take will matter: direct subsidies for renewables, for instance, would likely diminish the prospects for nuclear, while nuclear power would prosper under cap-and-trade or direct carbon tax legislation. Finally, nuclear power plants provide a specific type of energy, namely, electricity. Nuclear, then, competes directly with other elements of the electric sector: coal, natural gas, and renewable sources like wind, solar, and tidal power. Thus, changes that affect any one of these technologies can significantly affect the others: for instance, a large decrease in the price of coal may render nuclear less attractive.

This state of affairs means that the fortunes of the nuclear industry are, in part, determined by both changing electricity demands and the competitiveness of other electricity-generating technologies. To assess whether climate change will be a game changer for nuclear, it is necessary to answer three questions. First, will states or the international community take action on the climate? Second, what form will this action take? And third, given this policy change, what is the role of nuclear?

What Will Make Governments Act? It has proven difficult to reach consensus on a global scale, but individual countries and regions have begun to take steps to reduce emissions. What could speed up this process, or increase the salience of climate change with voting populations? First, some weather-related catastrophe could possibly focus public and political attention on the problem of climate change. Climate change is likely to increase the frequency and severity of extreme weather events such as floods, droughts, hurricanes, and heat waves. Extreme events like the 2003 heat wave that killed thousands in Europe will become increasingly normal, as shown in Figure 4.

However, the prospect of a single event that is a game changer for climate policy is unlikely, unless that event is merely a trigger that occurs in a political environment already leaning toward taking action in the climate arena. There are two reasons why a single event is unlikely to stimulate policy change. One is simply a matter of scientific uncertainty: our incomplete understanding of certain natural phenomena complicates our ability to make

Figure 4: Small Increases in Mean Temperature Cause Many More Extreme Events Owing to Higher Temperatures and Their Consequences



Source: Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report, Box TS.5, Figure 1, "Schematic showing the effect on extreme temperatures when the mean temperature increases, for a normal temperature distribution." Figure © IPCC 2007: WG1-AR4; used here with permission.

specific predictions about the effects of climate change. Hurricane formation, in particular, depends on sea surface temperature, but also on a variety of other factors, including monsoon distribution, wind shear, El Niño/La Niña oscillations, and water vapor formation. The second serious problem is a matter of attribution: weather- and climate-related events occur against a natural backdrop of variability. While it may be possible to understand the altered probability distributions of these events in a warming world, it will never be possible to fully attribute any single event to climate change.

If single events are unlikely to prompt large-scale government action, perhaps specific regional predictions may compel policy-makers to act in order to mitigate threats to their territories or economic interests. Unfortunately, while such regional predictions can be made with a (currently modest) degree of assurance,[40] it is difficult to provide decision-makers with precise information about the timescale and severity of the changes. Because greenhouse gases are well mixed in the atmosphere, and because so many components of atmosphere-ocean circulation are affected by large-scale processes, climate models are necessarily global. As a result, vast processing power is needed to run simulations, and global climate models operate on a coarsely resolved grid. Subgrid scale processes are parametrized; that is, their effect is modeled from available data. As processing power improves, the resolution can be made finer, but no model can capture all the intricacies of the climate system at finely resolved spatial and temporal scales. Because of this uncertainty, regional climate

40. Susan Solomon, Dahe Qin, Martin Manning, Zhenlin Chen, Melinda Marquis, Kristen Averyt, Melinda M.B. Tignor, and Henry LeRoy Miller, Jr., *Climate Change 2007: The Physical Science Basis* (New York: Cambridge University Press, 2007), chap. 11.

change may not be viewed as an imminent and tangible threat meriting immediate response, but as a non-urgent global problem awaiting negotiated international solutions.

In the absence of a game-changing single event or set of predictions, economic considerations may contribute to a change in climate policy. The direction and magnitude of such change, however, remain uncertain. In the United States and China, an abundance of domestic coal makes it an inexpensive and secure source of electric power, at least if negative externalities are not taken into account. While other countries may not have vast domestic deposits of coal, it remains relatively easy and inexpensive to obtain on the international market. The sheer size and maturity of the coal industry means that it can often effectively resist change. Hydrocarbon resource constraints in general are unlikely to play a major role in traditional electricity generation over the timeline of this study: new discoveries of natural gas have increased known reserves by as much as a third, while petroleum is not heavily used for electricity in the developed world. The current economic situation in the developed world has also lowered demand for electricity and impeded the construction of new power plants. However, regulations at the state level in the United States have created growing markets for low-emission technologies, and demand for inexpensive "clean" energy is increasing abroad. Although attempts to recast climate legislation in terms of economic competitiveness or "green jobs" have met with mixed results, the bipartisan effort to defeat California's Proposition 23, an attempt to repeal a statewide cap-and-trade system, successfully framed climate action as necessary to innovation and may mark a turning point. Outside the United States, China is aggressively developing renewable technology (in conjunction with ambitious fossil fuel and nuclear efforts), and European countries, particularly Germany, are poised to be major players in solar and wind energy. A desire to anticipate and compete in a future low-carbon world may lead more governments to incentivize clean-technology research and development, and would provide an economic impetus for emissions-control legislation.

Also unclear is whether binding international agreements among major emitters that would require domestic action to cut greenhouse gas emissions will come into force. Negotiations continue but have thus far been unsuccessful, with developing countries concerned about questions of fairness and the United States, in particular, reluctant or unable to commit to reduction targets. In several major countries, the priority given to climate change actions has dropped significantly in the past three years.[41] These developments, coupled with the relative weakness of international institutions, make it difficult to imagine a viable and binding international agreement coming into force any-

41. Stefan Theil, "A Green Retreat: Why the Environment is No Longer a Surefire Political Winner," *Newsweek*, July 12, 2010.

time soon. However, combinations of sustained grassroots pressure, political leadership, support from the business community, and economic incentives have resulted in a patchwork of different policies at national and subnational levels. The question for nuclear power is, how dependent is nuclear power on the likelihood and form of government action about climate change, at the local, national, and international levels?

What Form Could Climate Action Take? It is unclear how and if local policies will constitute a global emissions control regime, or what best practices may be adopted widely; still, it is instructive to examine common forms of regulation in order to determine the consequences for nuclear power. We can divide these policies into three rough categories. The simplest method involves taxing greenhouse gas emissions directly. A carbon tax has the advantage of addressing emissions while encouraging market-based development of new technology, and is a policy favored by many economists. Directly pricing carbon is likely, in the short term, to favor proven low-carbon base-load power technologies, of which nuclear is the primary example. Because of the long lifetimes of power plants, the consequences of these short-term decisions are likely to be favorable for nuclear power in the long term. In fact, a carbon tax could, at least in the United States, finally lead to the vaunted nuclear renaissance predicted by many experts.

Because of the prevalence of fossil fuels, a direct carbon tax is likely to increase electricity rates in the short term, provoking popular resistance. Even revenue-neutral taxes may leave their architects vulnerable to the attacks of political opponents. As a result, legislation in Europe and the United States often follows a cap-and-trade model, whereby the government issues a finite amount of permits to emit a certain substance. These permits can then be traded or sold, creating a market for emissions. Such policies have the advantage of determining a specific limit for emissions, while a tax on carbon may have to be adjusted several times to attain an emissions target. On the other hand, cap-and-trade regulations have proven difficult to design and even more so to implement. If the cap is set too high, then permits lose value; if too low, the price of energy can rise unacceptably. Allowing participants to purchase offsets—for example, through the “clean development mechanism” provided for in the Kyoto Protocol and practiced by some countries in the European Union—may lead to little or no net reduction in emissions from developed countries, and to reduced incentives to curb emissions in developing countries. The consequences for nuclear power in a cap-and-trade regime would therefore likely be similar to its growth under a carbon tax, but would depend strongly on the price and volatility of these carbon permits.

The third category of policies involves direct subsidies of low-emission technology. These subsidies come in several forms. Feed-in tariffs require utilities to purchase a set amount of electricity from renewable sources by guaranteeing a price for renewable energy over a specific time period, while renewable portfolio standards require utilities to supply a given percentage of total demand from designated renewable sources. While these approaches may facilitate the rapid introduction of otherwise prohibitively expensive technology, they do not necessarily encourage the development of new and more cost-competitive technologies. Additionally, policies of this type vary in the technologies they choose to subsidize because the definition of "renewable" or "low-emission" is open to interpretation. Is large-scale hydroelectric power, with its attendant environmental concerns, a "renewable" source of energy? Are biofuels, some of which promise to reduce emissions relative to gasoline but require vast land and water resources and also have poorly understood environmental effects, worthy of subsidy? Nuclear energy, in particular, falls into a gray area. Consider, for instance, that of the more than thirty U.S. states that have adopted renewable portfolio standards, only Ohio classifies nuclear technology as renewable. The consequences of these forms of subsidy for nuclear power will therefore depend on its classification and whether it is perceived as a clean technology.

What will be the Consequences of Government Climate Action for Nuclear Power? Such regulations have the potential to transform the entire energy sector, of which nuclear power is only a part. Game changers for other energy sources may thus be game changers for nuclear power by proxy. Changes in the electricity sector specifically will have the most direct impact on nuclear power. Game changers for petroleum, such as price shocks, drilling restrictions, or advances in refining technology, are unlikely to be direct game changers for nuclear power, at least in the developed world, where oil plays little to no role in electricity generation, unless electric vehicles achieve a high level of market penetration. In that case, demand for oil will be reduced, and the demand profile for electricity will change dramatically. Nuclear power will be affected by changes in the oil industry only insofar as those changes create incentives
to electrify transport.

If a price is placed on carbon emissions, coal, the most common source of energy for electric power worldwide, will be the most affected, because coal-fueled power plants emit the most greenhouse gases per kilowatt-hour. Had the Waxman-Markey bill put before Congress in 2010 become law, the Environmental Protection Agency (EPA) price for carbon emissions permits would have ranged from $15 to $70 a ton, high enough to justify closing coal-fueled power plants. Carbon capture and sequestration (CCS) could in principle reduce or eliminate those emissions; a large research and development effort is devoted to studying that possibility. Many questions remain about the long-term stability and safety of geologic storage and the effects that a large sudden release of stored carbon dioxide would have on the climate. In addition, even if present techniques prove to be successful on a technical basis, CCS would lead to at least a 25 percent increase in cost and

Table 4: Life-Cycle Greenhouse Gas Emissions, per Gigawatt-Hour (GWh), for Various Sources of Energy

Energy Source	Tons CO_2 Equivalent/GW
Lignite	1,000–1,400
Coal with Flue Gas Desulfurization	800–1,100
Coal with Flue Gas Desulfurization and Carbon Capture and Sequestration	150–200
Natural Gas Combined Cycle	400–500
Natural Gas Combined Cycle with Carbon Capture and Sequestration	200–250
Photovoltaic	Small–100
Hydro	Small–100
Biomass	Small–50
Wind Offshore	Small–30
Wind Onshore	Small–20
Nuclear	Small–50

1 GWh = 1 million KWh. Source: Adapted from Intergovernmental Panel on Climate Change, Fourth Assessment Report, vol. 3, "Mitigation of Climate Change" (2007).

decrease in electrical output per ton of coal. Nevertheless, given the vast investment in coal plants around the world, retrofitting coal-fueled power plants with CCS, should it prove to be a safe and reliable technology, could become an attractive option (see Table 4).

With a price on carbon emissions, power plants fueled by natural gas gain an advantage over those fueled by coal. Gas combustion generates about half the CO_2 emissions of coal combustion. Additionally, modern combined-cycle gas plants are much more efficient in terms of electricity generated for a given amount of fuel used than coal or nuclear plants, and gas plants are generally cheaper to build and license than nuclear plants. The overall levelized cost of a kilowatt-hour from a gas plant depends on the price of natural gas, but is generally competitive with coal and nuclear. However, the availability of gas depends on location; major investments are needed either for pipelines or for liquefied natural gas transport; care must be exercised to prevent leakage of the natural gas, itself a greenhouse gas; energy security concerns may make gas unattractive in certain areas (such as parts of Europe); and environmental concerns could curb shale-gas drilling techniques. Nevertheless, the discovery of new natural gas reserves in the United States could be a game changer for nuclear power and the electricity industry as a whole.

In an emissions-constrained world, the most direct competitors to nuclear energy are hydroelectric power and renewable energy sources such as

wind, solar, and tide. These technologies also generate no carbon dioxide during operation, and they do not suffer from the negative perceptions attached to nuclear energy in the United States and elsewhere. However, the expansion
of hydroelectric power is limited by both the availability of sites and environmental concerns. Moreover, renewables have potential drawbacks that could make nuclear power appear relatively attractive. First, generating large-scale power from wind, sun, or water requires a significant amount of surface area. Solar thermal, hydro, and biofuels also require large quantities of fresh water. Because renewables generate a small proportion of the world's electricity, these concerns are relatively minor at present. However, as these sources begin to play a larger role in electricity generation, the larger scale may pose unexpected problems. Second, because wind farms and large solar installations tend to be located far from population centers, aggressively pursuing renewable sources means that, in many cases, new transmission lines will have to be built. While grid extension and modernization efforts are ongoing in developed countries and surging in China, large private and public investments are necessary. In addition, it is often difficult to obtain construction permits for high-voltage transmission lines. Barring significant changes at local, state, and national levels, the transmission problem will continue to impede renewable development, perhaps to the benefit of nuclear power. Finally, renewables provide intermittent power, and instantaneous generation is often difficult to predict owing to variable wind speeds, cloud cover, and wave heights. In the absence of reliable storage technologies, this sometimes unpredictable variability requires system operators to make special provision for integrating varying generation into the grid, and the proportion of total electricity that can be provided by these sources is limited. Nuclear, by contrast, operates at high capacity, providing a steady supply of constant power. The invention of inexpensive, viable, efficient storage mechanisms could greatly increase the appeal of renewable sources, perhaps to the detriment of nuclear power.

Nuclear Power and the Grid

Paradoxically, the base-load characteristic of nuclear power may put the technology at a competitive disadvantage in the future. This is because of potential changes in transmission and distribution that could be implemented to aid the integration of renewable sources. The development of the electricity sector in most low- and medium-income countries (and even some wealthy nations) is constrained by the capacity of the existing electric grid, and this will have consequences for nuclear power. Presently, the only way to achieve economies of scale for nuclear power is to utilize large capacity plants (above 500 MWe). Such large plants may not integrate well into existing electric grids, leading to a push for development of smaller modular reactors in an attempt to achieve economies of scale at the manufacturing level. Even smaller reactors, however, may be difficult to integrate into the "smart grids" of the future, which may be designed to handle the highly intermittent power generated by renewable sources. If renewables such as wind and solar are heavily subsidized, or if government standards mandate that a certain percentage of electricity must be generated by these technologies, it will be advantageous to utilize installed renewable capacity to its fullest potential. As renewable capacity increases, it is conceivable that the function of other technologies, such as nuclear, gas, and coal, will be to meet the residual demand not met by renewables.

Changes in Supply and Demand

The nature of electricity demand may change as well, particularly if large swaths of the transportation sector are electrified. If this occurs, power plants normally used for base-load may be forced to operate in load-following mode, delivering variable power to meet peaks and troughs in supply. This is technically possible, if complicated by the difficulty of quickly increasing or decreasing output and the need to prepare for unpredicted demand peaks. France, which depends on nuclear power for more than 80 percent of its electricity, operates some nuclear plants in load-following mode out of necessity. However, the economic case for nuclear plants is often based on their high capacity factors—over 90 percent for U.S. plants in 2009. This is because technologies that derive most of their levelized cost from amortizing initial capital investments, such as nuclear or hydro, are at a financial disadvantage in following a variable residual load compared to technologies that derive most of their levelized cost from fuel, such as gas. For the former technologies, one is paying the bigger share for time over which the money has been advanced and time keeps flowing by; for the latter, the bigger share of the cost is for gas, which can be turned off. If renewables are implemented on a large scale, residual demand may often drop below the capacity of existing nuclear plants: one study has found that German residual demand, for example, would drop below 20 GW more than fifty times a year by 2030, and would occasionally fall as low as zero. The economic justifications for nuclear power appear very different given these periods of low residual demand, and it is not clear that given all the attendant problems of a nuclear plant, utilities will be eager to invest in comparatively low-capacity plants.

In summary, the introduction of policies setting a significant price on emissions will favor all the low-emissions technologies: nuclear, renewables, and hydroelectric. Which will be *most* favored will depend on four major variables:

1. Relative costs under the foreseen operating conditions, including land and water costs;
2. Investment in and design choices for the electric grids (these two variables are highly interdependent);

3. Both real and perceived environmental impact of the technologies; and
4. Public sentiment as it evolves during deployment regarding all the technologies, but especially nuclear power.

The most obvious game changer for nuclear energy and for its competitors would be the development of a clean, safe, inexpensive, and widely deployable technology for electricity generation. Fusion fits the bill, but despite the scientific advances discussed above, it is unlikely to be widely commercially available in the timescale we consider. The list of potential disruptive technologies is long, and categorizing specific possible advances is beyond the scope of this paper. However, any game-changing technology must address the shortcomings of current technologies: the waste, expense, and proliferation concerns of nuclear, and the intermittency, high cost, or resource constraints associated with renewables. It requires no special understanding of current research and development to appreciate these problems, and to anticipate technologies that may solve them.

STRATEGIES FOR GAME CHANGERS

No one can think of or plan for every game changer. Even if it were possible to list all separate events and developments that could affect nuclear power in the future, the combination of them would lead to unforeseeable situations. Nevertheless, the survey of the previous sections will, we hope, narrow the range of "unknown unknowns." It casts light on the causes and limitations of current planning as well.

Given this necessarily partial survey, the question remains: what can be done about game changers? Four main factors complicate the ability to answer this question:

1. There is considerable uncertainty and, in many cases, ignorance about both the probability and the consequences that can be assigned to the individual game changers considered. Game changers are not necessarily "black swans," or events that are assigned low probability based on a known distribution. Often, their likelihood is unknown because the probability distribution is so uncertain. It is not possible, after all, to construct a mathematical measure of terrorist motivations, or to quantify the probability of a future event that focuses popular attention on nuclear power. The normal approach of assessing risk and then determining how much to spend hedging against that risk is in many (perhaps most) cases not available or necessarily applicable.

2. There is also considerable uncertainty about the timescale on which

the game changers could occur. Some potential game changers stem from ongoing events (climate change, increased export capabilities from China and other Asian countries). The unknown game changers in those cases are the reactions to those events: their form, timescale, and magnitude. Other potential game changers may or may not occur in the distant future; viable commercial fusion is one such example. Still others could occur at any time, such as the success of small modular reactors or a terrorist strike.

3. The greatest complication for analysis comes from the question of whose strategy will capture the most interest and command the most influence. If we define strategy as a combination of plans and decisions that can lead or is leading to a series of concerted actions, a number of the major actors in the nuclear energy field—governments and private firms—seem to have strategies. In the following subsection, we will characterize some of those strategies.

4. If a study of game changers is to produce actionable policy recommendations, it is important to define the desired outcome. The strategies of individual actors are designed to achieve differing, and sometimes conflicting, goals. Some game changers—an accident or attack, for example—will have universal negative consequences, but many will benefit some actors at the expense of others. Therefore, it is necessary to identify issues of common interest and promote those strategies that best deal with the game changers in those areas.

Having looked at nuclear energy around the world and at the global and local factors that could change prospects for nuclear energy as a whole, one may ask whether an analysis such as this one leads to a global strategy. If so, is there an actor that can carry it out? We will consider those two questions at the end of this section.

Strategies of Individual Actors

Our survey of national programs shows some definite strategies for development of the nuclear energy industry in various countries. China, South Korea, France, Russia, and to some degree, Japan have committed to major buildup and export programs to help support and make large domestic programs more profitable. The United States remains very much in the export business, but the lack of both a U.S.-only reactor builder and a generally agreed-upon national policy for nuclear power has prevented a clear strategy from emerging. India is committed to a large increase in nuclear power as well as other forms of power. Other states have announced that they are either continuing or reconsidering their policies.

How do these state strategies deal with the possible game changers outlined in this paper? In the following section, we argue that certain game changers would be either desirable or very undesirable for all actors in the nuclear game and examine how the strategies of states can prevent or bring about these events.

Preventing Attacks and Accidents. Ensuring reactor safety and keeping nuclear material out of the hands of terrorists are universal goals; accidents or attacks can have only negative consequences by any metric. National strategies for dealing with possible game-changing events stemming from terrorism, accidents, and diversion from nuclear reactors are agreed in principle if not always carried out in practice. To varying degrees, most countries cooperate in international attempts to prevent nuclear terrorism and nuclear trafficking. There is also international cooperation on improving safety through better reactor design and operational procedures and operator training. These are avowed goals of all national strategies. Implementation is checkered, and it is difficult to assess the extent to which those goals are translated into effective practice in some countries. Similarly, agreement on better safeguards through putting the IAEA Additional Protocol into force is a work in progress, despite the fact that this is an avowed goal in most national strategies.

Controlling the Spread of Sensitive Nuclear Material. There is no agreement yet on limiting the spread of sensitive facilities to discourage nuclear weapons proliferation. With the exception of a few suspected proliferators, most actors in the nuclear power arena have an interest in limiting the spread of sensitive nuclear material. However, the difficulty inherent in balancing the right to nuclear power technology within the parameters of the nonproliferation regime has led to wide disagreements on how best to control fissile material. It can be argued that because such proliferation has not proven to be a game changer for nuclear power, agreement on such limits has no place in a strategy to deal with game changers in nuclear power. But that argument is seldom explicitly made, and is perhaps shortsighted. The spread of enrichment or reprocessing nuclear facilities could lead to more latent nuclear-armed states: states that could fairly quickly acquire nuclear weapons, perhaps on a timescale as short as months. That development, coupled with the entry of new exporters into the market, could make for a very different marketplace. Optimistically, it could lead to new and more broadly accepted agreements on safeguarding nuclear power; pessimistically, it could lead to fragmentation of the market along political lines or, worse, to a marketplace in which effective steps are no longer taken to limit the dangers of nuclear weapons.

Safer, More Secure Reactors. Among states using nuclear power, there is general agreement about the desirability of safe and secure nuclear facilities. The implementing tools (for example, the World Association of Nuclear Operators standards setting, the adoption of standards concerning safe design and siting by the U.S. Nuclear Regulatory Commission and other such regulators, and, to different degrees, the various IAEA national agreements) can be viewed as adding up to a strategy, albeit an evolving one necessarily subject to national variations.

Beyond these steps, technological developments that render nuclear facilities safer and more proliferation-resistant or that reduce waste are in everyone's interest. Strategies to deal with technological game changers consist mainly of R&D by private entities with government support, at paces ranging from accelerated to somnolent. The disparity in national R&D strategies could in time lead to major new actors in the nuclear market, with China and India particularly active. Historically, new technologies have taken decades to penetrate the electricity generation and transmission markets. R&D investments are made largely by the state in China, India, and Russia, while in France R&D is shared between the public and private sectors. In the United States and some other Western countries, investing in such developments as small modular reactors, laser enrichment, and other innovations is mainly the province of industries and utilities.

In addition, two major changes in the nuclear fuel cycle are currently being studied by governments: the thorium-based fuel cycle in India and the final disposal site for spent fuel or parts of it in the United States and elsewhere. If it can be economically implemented, the thorium-based fuel cycle could make India's nuclear program independent of external uranium suppliers and could also broaden the appeal of its exports. The U.S. program to find a new disposal site stems from a domestic political standoff and reflects the lack of a generally understood and supported strategy for nuclear power in the United States.

Preventing or Mitigating Climate Change. The reaction of state governments to climate change is variable and generally quite slow. Most industrialized states are reconsidering their domestic energy mix in light of climate change, with differing results. Investments in efficiency and conservation vary from country to country. Thus, there is no global agreement or strategy on emissions, although there may be international agreement on limiting the use of some of the more deleterious climate change agents, such as HFCs, where commercial opposition is less strong.[42] There has been a general move toward greater use of renewables, but their higher cost at a time of recession and perceived high government indebtedness is limiting these moves in some countries. At most, ongoing and planned actions will decrease the rate of growth of greenhouse gases in the atmosphere, but they will not limit the anticipated warming to some predictable value, let alone reverse it. It is difficult to see how this pace of change, if continued, can amount to a game changer for nuclear power—at least not until the consequences of climate change become

42. John M. Broder, "A Novel Tactic in Climate Fight Gains Some Traction," *The New York Times*, November 8, 2010, http://www.nytimes.com/2010/11/09/science/earth/09montreal.html?_r=1&scp=1&sq=HFC%20emissions%20ozone%20hole&st=cse.

sufficiently obvious and damaging to support a global consensus on a remedial strategy.

Besides governments, industries and utilities also have strategies, which may generally be classified as "minimax strategies": that is, strategies whose dominant objective is to avoid worst possible outcomes, namely, bankruptcy. Nuclear enterprises today fall into two camps: those that can rely on enough government support or sponsorship to prevent bankruptcy and those that cannot. The former category has shifted the worst risk to government, while the latter category, which includes most U.S. utilities and some others, faces an uncertain financial and regulatory environment. This is especially true with regard to future externality pricing of emissions; as a result, investors are reluctant to commit to financing expensive new power plants. This reluctance applies (to a greater or lesser degree) to all but the most essential investments in the electricity sector. Anything that would reduce investor uncertainty and make realistic risk assessments possible could be a game changer for nuclear firms, in particular, and the electricity sector, in general, as well as for the country in which they operate. Pending such an eventuality, minimax strategies are likely to dominate plans in the private sector.

Global Strategies

The brief survey we have just laid out illustrates the areas in which goals are shared between many actors, making a global strategy possible, at least in principle. Such a strategy should address universal common goods, including security and the global environment. Technological and local economic opportunities and risks are more effectively addressed by the private sector and individual governments, but a global strategy would provide for the transfer of innovations that make nuclear power safer and reduce the risk of accident or diversion.

In brief, avoiding accidents and terrorism is generally agreed to be a common good, and the elements of a common strategy are in place, if not always effectively implemented. As noted above, states and localities vary in their approaches to the global environment, particularly where climate change is concerned; despite much negotiating, we are still short of a global approach to such problems. Avoiding nuclear weapons proliferation is also considered a global common good by the vast majority of states, but the steps to implement a common strategy, such as limiting the spread of enrichment and reprocessing facilities and accepting more intrusive safeguards, are not generally agreed upon. To obtain agreement among the states involved in nuclear power use or trade, a common strategy will have to provide for continued competition in the provision of internationally traded nuclear supplies, such as enrichment services or uranium ore. It must also provide some safeguards against politically based interference with international nuclear trade.

Economics plays an ambiguous role in the potential spread of sensitive facilities. The very large enrichment and reprocessing plants needed to provide economically for a fleet of power reactors require multibillion-dollar investments and the development of advanced technological capabilities in areas as varied as metallurgy and remote operations. As long as both buyers and sellers of enrichment and reprocessing services have access to a competitive international market free of political restrictions, so that they can buy enriched or reprocessed fuel at market prices, it may be some time before the enrichment and reprocessing capacities of the major nuclear power users are matched by any significant number of new national efforts. On the other hand, the enrichment and reprocessing requirements for even a few power reactors far exceed what is needed to provide materials for a few nuclear weapons per year. States that wish to have a latent nuclear weapons capability do not need to make the large investments in enrichment or reprocessing required for an economical civilian capability.

The United States and states that share its priorities with regard to avoiding nuclear weapons proliferation and safeguarding civilian nuclear operations face a problem in dealing with potential proliferators. To the extent that the United States and allies limit international access to nuclear services on grounds of proliferation risk, they also motivate the spread of sensitive facilities, which even on small scales can provide a state with at least a latent nuclear weapon capability. In the past, the United States and other states interested in limiting nuclear weapons proliferation held enough of a monopoly on the needed materials and technologies so that supply constraints were partially effective in delaying or preventing weapon proliferation. This near-monopoly is decreasing due to both the entry of new suppliers that do not or may not share the U.S. priorities and the wider availability of the needed technologies. Even a poor, isolated state such as North Korea has succeeded in making enough plutonium for several nuclear weapons and, more recently, in building what appears to technically trained observers to be a modern enrichment facility.[43] The strategies proposed to deal with this problem range from continuing attempts encouraging suppliers to agree on limiting or conditioning supplies, despite probable growing ineffectiveness, to trying to enlist more cooperation by leading a move to universal nuclear disarmament. It is not clear that any of these strategies will be effective. It is also not clear whether success or failure in dealing with the problem of weapons proliferation will affect the future of nuclear power.

43. Alex Spilius, "North Korea has Built Sophisticated Uranium Enrichment Facility, US Scientist Says," *The Telegraph*, November 21, 2010, http://www.telegraph.co.uk/news/worldnews/asia/northkorea/8149865/North-Korea-has-built-sophisticated-uranium-enrichment-facility-US-scientist-says.html.

RESEARCH DIRECTIONS

In this section, we identify four research directions that could usefully build on the work reported in this paper. These are not the only possible directions: a great deal of research has been done and is continuing on the topics discussed in the previous sections. Instead, these suggestions are natural extensions of our work that should, in our judgment, receive study beyond what has been done already.

Are There Better Strategies to Deal with Game Changers?

Early in this study, we pointed out that the record of prediction in the energy sector, in general, and the nuclear energy sector, in particular, is poor. In part, this track record is inevitable, given that some game-changing events cannot be foreseen. Further, it can be ascribed to unfamiliarity with the advantages and disadvantages of an entirely new technology in the early years of the nuclear age. But this deficiency could be partly ascribed to ignorance, bias, or tunnel vision, and may therefore be subject to improvement. This leads to the question of whether there are better strategies to deal with game changers.

In the previous section, we discussed briefly some current strategies, and we noted where individual state strategies were in harmony and where they were not. We also noted that for many game changers, no quantitative risk assessment is possible. We also pointed out some of the factors that make devising a strategy for game changers difficult. We did not, however, systematically examine possible better strategies in terms of their acceptability to planning organizations and their cost effectiveness. For instance, what strategies are available to the United States to prepare for a changing nuclear market, one with new buyers, new sellers, and new sales arrangements? What can the United States and its allies do to prepare for the demand for sensitive facilities, possibly much less expensive ones, in different countries? As they multiply their use of nuclear power by large factors, what can developing countries do to prepare for the near-certainty of a "normal accident"?

Such analyses, combining economic, technical, and political factors, would materially assist the national planning processes. An analysis can be carried out at a general theoretical level, assessing what planning techniques are available for the different varieties of what we have called game changers, or more specialized analyses can be carried out on any of the problems listed above and similar ones.

What International Agreements to Deal with the Possible Spread of Sensitive Nuclear Facilities Could Receive General International Support?

In addition to the nuclear weapons states and some major nuclear power users, states as varied as Brazil, South Korea, and Iran have sought or are seeking to build enrichment and/or reprocessing facilities. Far more so than nuclear reactors, those facilities are dual-purpose, suited equally to make fuel for reactors and for nuclear weapons. Several proposals have been made to prevent the spread of these facilities and the associated risks of nuclear weapon proliferation, actual or latent. Those proposals range from restricting the number of states with such facilities to the present ones, restricting the facilities to internationally owned and managed ones, and having the IAEA or another international organization own and manage a stockpile of enriched uranium for reactors, among others.

Those proposals have not received the near-universal international support that is needed to make them successful. Clearly, states that want to acquire nuclear weapons or be in a position to build them quickly are unlikely to agree willingly to restrictions on any of the key facilities. Thus, no proposal aimed at guaranteeing that sensitive facilities are used only for civilian purposes would have had the support of North Korea, for example, in the past decades. But an international agreement that has the support of the near entirety of parties to the NPT that do not want nuclear weapons would strengthen that treaty, and with it the norm against nuclear weapons proliferation.

To secure that support, an agreement would have to satisfy both the economic and the political criteria of importance to NPT states-parties. Among others, these criteria are likely to include the preservation of a competitive market in enrichment services and the development of a competitive market in reprocessing services, should the demand warrant it; access to those markets that does not depend on the relations of a state with a major power; and continued freedom to innovate on the part of private as well as government organizations. To our knowledge, there has been no systematic study of how effective existing safeguards and other possible safeguards for sensitive facilities would be from the combined economic and political standpoint that we suggest.

What will the International Nuclear Market Look Like in Twenty to Thirty Years?

On a number of occasions in this paper, we have pointed out factors both internal to the nuclear market and external to it that are likely to change that market and its economic and political outlook. Among the factors internal to the market are the possible development of much lower cost suppliers, such as China; the broadening of demand to some developing states now without nuclear experience; a decreased emphasis on the security aspects of the international nuclear trade such as could follow lessened U.S. influence on that trade; and perhaps increased incidence of accidents as countries new to nuclear power expand their nuclear operations. Factors external to the nuclear market include the possible development of much less expensive renewable sources of electricity and electricity storage, changes in the electric grid to accommodate those sources, and changes in climate.

To our knowledge, no systematic study exists of the possible directions of the nuclear power market, evaluating both economic and political consequences of those changes under a variety of assumptions. The study would necessarily be international in scope to reflect the nature of the market. Such studies probably exist examining the market from the standpoint of a particular company, but they are not generally publicly available and do not inform other market participants. A scholarly study or studies such as we outline above would better prepare the various actors in the market to meet eventualities.

What would be the Technical, Economic, and Security Implications of a Decision by the United States to Close Its Nuclear Fuel Cycle?

To date, closing the nuclear fuel cycle has not been deemed economical by the United States; efforts in that direction were ended on both economic grounds and the grounds that a "plutonium economy," such as could arise from closing the cycle, would increase risks of nuclear weapons proliferation. Other countries (France, Russia, Japan) have made different assessments, and still others (South Korea) are considering their options. The issue has been much studied.

The new study we suggest in this area would look at the problem afresh, taking into consideration three new factors:

1. The possibility of better technologies for both reprocessing and enrichment, as well as entirely new cycles, such as the India-sponsored thorium-based cycle;
2. The closing of the Yucca Mountain disposal site and the ongoing study to find new disposal methods and sites; and
3. The future shape of the international market for both nuclear power and the demand for nuclear facilities.

CONCLUSIONS

Present-day forecasts for nuclear power, based on the accepted no-surprise scenario, appear likely to repeat the mistakes of past planning. In particular, there is no accepted, integrated framework to incorporate and mitigate game changers and their consequences. Some of these consequences may be limited: the inability of companies to foresee and capitalize on emerging technologies may affect them negatively, but is hardly uncommon or disastrous. Some potential consequences, however, could be severe—and could have ramifications far beyond the area of nuclear power. After all, nuclear power is unique in the problems it poses: worst-case scenarios involving the theft of weapons-grade material or a severe accident at a nuclear plant would arguably be among the most catastrophic to arise anywhere in the energy sector. It is therefore imperative to devise effective strategies for thinking about game changers. How might this be accomplished, and what is missing from current plans?

First, an overemphasis on rare "black swans" has prevented planners from appreciating the full range of game changers. Even plans that explicitly account for sudden surprises suffer from an incomplete understanding of what it means for an event or development to "change the game." As we have shown, game changers are not simply unanticipated low-probability events, but can also be ongoing, evolutionary changes or high-probability "normal accidents." Undoubtedly, the ascendancy of China in the nuclear industry, the emergence of new nuclear markets, and large-scale action on climate change may have serious and unanticipated consequences for nuclear power. These evolutionary changes may prove to change the game in far more unexpected and radical ways than sudden, surprising shocks.

Second, as we have shown, game changers are possible in almost all aspects of the nuclear power field, from technological innovations in the fuel cycle to regulation of greenhouse gases to changes in politics among and within the great powers. It is a fruitless exercise to predict the exact events or innovations that will shape the future of the field. Instead, it is useful to identify the outstanding problems that future innovations might address. Advances in reactor technology, for example, are difficult to predict, but in order to represent an improvement on current technology they must make nuclear power safer, less expensive, more proliferation-resistant, or must reduce the volume or change the composition of spent fuel. We have identified the shortcomings of present-day technology that impede progress toward these goals rather than assess the suitability of various technologies on the horizon.

Finally, the existence of many actors with many agendas should not obscure the fact that there are many outcomes that are universally positive or negative. A nuclear accident, for example, benefits no one, and most countries have a strong incentive to prevent fissile material falling into the hands of terrorist groups. Therefore, it is possible to identify universal public goods and shared goals and to work to coordinate national and industry strategies to realize them. Even when strong disagreements exist—on the structure of a future nonproliferation regime, for example—it is helpful to identify the exact areas of conflict, and to highlight areas of agreement. Most states agree on the need to curb proliferation but disagree on how to balance this with the right to peaceful use of nuclear power. Considering the consequences of game changers such as this one can help provide a useful way to proceed in present discussions of nuclear energy and clarify common future goals.

Contributors

Kate Marvel is the William J. Perry Fellow in International Security at the Center for International Security and Cooperation at Stanford University. She received a Ph.D. in theoretical physics from the University of Cambridge.

Michael May is Professor Emeritus (Research) in the School of Engineering at Stanford University, where he is also a Senior Fellow with the Freeman Spogli Institute for International Studies. He is former Codirector of Stanford University's Center for International Security and Cooperation and is Director Emeritus of the Lawrence Livermore National Laboratory. He has held a number of government advisory positions, was a member of the U.S. delegation to the Strategic Arms Limitations Talks, and is a Fellow of the American Physical Society and the American Association for the Advancement of Science. May received the Distinguished Public Service and Distinguished Civilian Service Medals from the Department of Defense, and the Ernest Orlando Lawrence Award from the Atomic Energy Commission, as well as other awards. His current research interests are in nuclear security, energy, environment, and terrorism, and in the relation of nuclear weapons and foreign policy.

Participants

Game Changers for Nuclear Energy

A workshop cosponsored by the American Academy of Arts and Sciences and the Center for International Security and Cooperation (CISAC) in the Freeman Spogli Institute for International Studies at Stanford University, held August 26–27, 2010, at Stanford University

Alex Alben
TerraPower Intellectual Ventures

Leslie C. Berlowitz
American Academy of Arts & Sciences

Edward Blandford
Department of Nuclear Engineering, University of California, Berkeley (now at Center for International Security and Cooperation, Stanford University)

Chaim Braun
Center for International Security and Cooperation, Stanford University

Louis W. Cabot
Cabot-Wellington, LLC;
American Academy of Arts & Sciences

Martha Crenshaw
Center for International Security and Cooperation, Stanford University

Phillip Duffy
Climate Central

Kimberly Durniak
American Academy of Arts & Sciences

Steve Fetter
Office of Science and Technology Policy, The White House

Kenneth Fowler
Department of Nuclear Engineering, University of California, Berkeley

Megan Garcia
The William and Flora Hewlett Foundation

Alexander Glaser
Woodrow Wilson School of Public and International Affairs and Department of Mechanical and Aerospace Engineering, Princeton University

Stephen Goldberg
Argonne National Laboratory

Alan Hanson
AREVA

Siegfried Hecker
Center for International Security and Cooperation, Stanford University

Thomas Isaacs
Lawrence Livermore National Laboratory; Center for International Security and Cooperation, Stanford University

Gordon Jarvinen
Los Alamos National Laboratory

Ronald Lehman
Lawrence Livermore National Laboratory

Michael Levi
Program on Energy Security and Climate Change, Council on Foreign Relations

Ning Li
TerraPower Intellectual Ventures; Berkeley Nuclear Research Center, University of California, Berkeley; School of Energy Research, Xiamen University

Kate Marvel
Center for International Security and Cooperation, Stanford University

Michael May
Center for International Security and Cooperation, Stanford University

Richard Meserve
Carnegie Institution for Science

Marvin Miller
Center for International Studies and Department of Nuclear Science and Engineering, Massachusetts Institute of Technology

Steven Miller
Belfer Center for Science & International Affairs, Harvard University

Warren Miller
Office of Nuclear Energy, U.S. Department of Energy

Edward Moses
Lawrence Livermore National Laboratory

Tom Mulford
Electric Power Research Institute

Per Peterson
Department of Nuclear Engineering, University of California, Berkeley

Ellen Petrill
Electric Power Research Institute

Burton Richter
SLAC National Accelerator Laboratory

Scott Sagan
Center for International Security and Cooperation, Stanford University

Robert Schock
Lawrence Livermore National Laboratory
(now at World Energy Council)

Sharon Squassoni
Center for Strategic and International Studies

James Sweeney
Precourt Institute for Energy, Stanford University

John Weyant
Department of Management Science and Engineering, Stanford University

The Global Nuclear Future Initiative of the American Academy of Arts and Sciences

There is growing interest worldwide in civilian nuclear power based on the recognition of its potential for meeting increased energy demands. But the spread of nuclear technology, in the absence of rigorous safety regimes, presents unique security risks, including the potential proliferation of weapons capabilities to new states, sub-national, and terrorist groups.

The American Academy's Global Nuclear Future Initiative is working to prevent this dangerous outcome by bringing together constituencies that historically have not communicated effectively—from government policy-makers to heads of nongovernmental organizations, from nuclear engineers to industry leaders, from social scientists to nonproliferation experts—to establish an interdisciplinary and international network of experts working together to devise and implement nuclear policy for the twenty-first century. Our overriding goal is to identify and promote measures that will limit the security and proliferation risks raised by the apparent growing global appetite for nuclear energy.

To help reduce the risks that could result from the global expansion of nuclear energy, the Initiative addresses a number of key policy areas, including the international dimension of the nonproliferation regime, the entirety of the fuel cycle, the physical protection of nuclear facilities and materials, and the interaction of the nuclear industry with the nonproliferation community. Each of these areas has specific challenges and opportunities, but informed and thoughtful policies for all of them are required for a comprehensive solution. We also recognize that "game changers," including natural disasters, terrorism, or other developments, could have a tremendous impact. These events could influence the safety and security of nuclear energy and are being identified and included in our deliberations.

American Academy of Arts and Sciences

Selected Occasional Papers of the American Academy

"Nuclear Reactors: Generation to Generation"
Stephen M. Goldberg and Robert Rosner

"Shared Responsibilities for Nuclear Disarmament: A Global Debate"
Scott D. Sagan, James M. Acton, Jayantha Dhanapala, Mustafa Kibaroglu, Harald Müller, Yukio Satoh, Mohamed I. Shaker, and Achilles Zaluar

"Multinational Approaches to the Nuclear Fuel Cycle"
Charles McCombie and Thomas Isaacs, Noramly Bin Muslim, Tariq Rauf, Atsuyuki Suzuki, Frank von Hippel, and Ellen Tauscher

"Challenges to Business in the Twenty-First Century"
Edited by Gerald Rosenfeld, Jay Lorsch, and Rakesh Khurana

"Science and the Educated American: A Core Component of Liberal Education"
Edited by Jerrold Meinwald and John G. Hildebrand

"Science and the Media"
Edited by Donald Kennedy and Geneva Overholser

"Do Scientists Understand the Public?"
Chris Mooney

"Education and a Civil Society: Teaching Evidence-Based Decision Making"
Eamonn Callan, Tina Grotzer, Jerome Kagan, Richard E. Nisbett, David N. Perkins, and Lee S. Shulman

"The Policy World Meets Academia: Designing U.S. Policy toward Russia"
Edited by Timothy Colton, Timothy Frye, and Robert Legvold

To order any of these Occasional Papers please contact the Academy's Publications Office.
Telephone: 617-576-5085; Fax: 617-576-5088; Email: publications@amacad.org