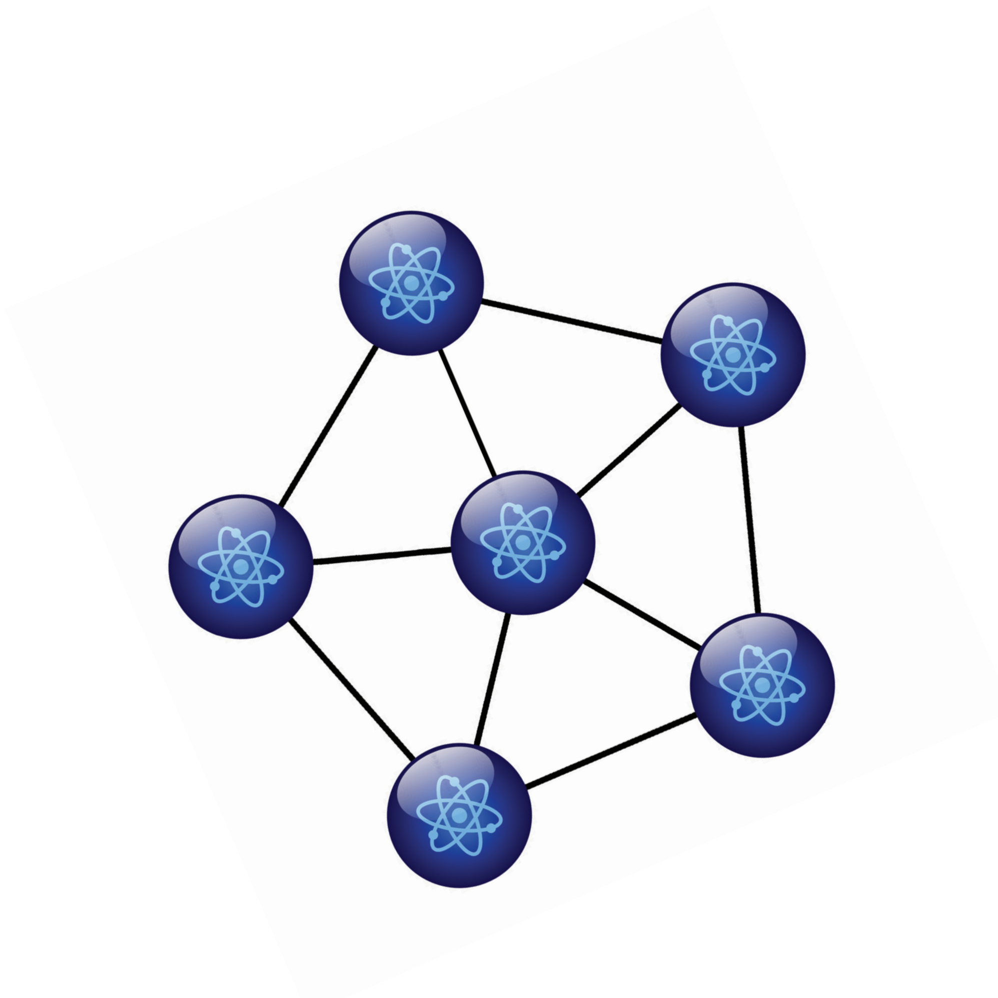
American Nuclear Energy at the Crossroads



By Gerald M. Stokes, Aristides A. N. Patrinos, John C. Houghton, Robert Bari, Paul Dickman, Alan S. Icenhour, Michael Lawrence, Kemal Pasamehmetoglu, Victor Reis, Robert M. Simon, and Elizabeth Turpen

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Printed in the United States of America.
17 1

Library of Congress Cataloging-in-Publication Data
Control Number: 2017960728

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Contents

Foreword

American nuclear energy stands at the crossroads between declining production and a robust future.

A dearth of new reactor construction and the pending retirement of aging reactors suggest that we will have little or no nuclear power before long. Is that a bad thing? Should we simply let prevailing economic forces determine our future energy technology mix?

Do national security concerns justify preferential consideration of nuclear energy? A declining nuclear power industry portends a loss of the nuclear expertise needed for U.S. leadership internationally of both nonproliferation efforts and safety initiatives.

Do climate change concerns strengthen the case? Nuclear power may be needed as a carbon-free energy option.

These are the questions that motivated this study.

Novim is a nonprofit scientific research group based at the University of California, Santa Barbara, that specializes in issues of global controversy. Novim is proud of its ten year history of summarizing the science behind these controversies without advocacy.

This report examines the above questions and delivers recommendations for some possible pathways for the future of nuclear energy in the United States. Novim is grateful to the scientists who came together to tackle this important subject, especially Dr. Gerry Stokes who led this study and Dr. John Houghton for his tireless efforts to make sure all the pieces came together.

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Executive Summary

The civilian nuclear power industry in the United States is in decline. Without immediate near-term action, the U.S. nuclear industry may essentially disappear in the next two to three decades. In recent years there were four nuclear power plants under construction in the U.S. The construction of two in South Carolina has been abandoned; the other two, located in Georgia, have been delayed with construction costs exceeding budget. Even with the completion of those two and expected life extensions for some existing nuclear power plants, nearly all operating units may be retired in the next twenty to thirty years. Adding to these challenges, the nuclear reactor supplier, Westinghouse, a subsidiary of the Japanese company Toshiba, has filed for bankruptcy. There are, at present, no alternative active U.S. licensed suppliers of commercial nuclear power plants.

Even with expected life extensions of the nuclear power plants, nearly the entire current U.S. nuclear fleet may retire in the next twenty to thirty years.

The decline could not be happening at a worse time. The capability being lost provides a key element of U.S. and international nuclear nonproliferation programs. U.S. nuclear know-how plays an essential role in understanding and responding to the nuclear weapons ambitions of Iran and North Korea. Risks of nuclear weapons proliferation are likely to rise as the number of nations with nuclear capability increases. The fuel cycle technology for nuclear power and nuclear weapons is essentially the same, so expansion of nuclear power raises the specter of increased risk for nuclear weapons proliferation.

Notably, several new nuclear energy producing countries will be added this decade. If the U.S. does not supply nuclear technology to these countries, it will have much less influence over their fuel-cycle decisions. The U.S. has gained knowledge from its own nuclear weapons programs (See text box, Hanford: The Application of DOE Capabilities to Address National Security Needs, in Chapter 1, page 7) to generate ideas and information that have helped detect and understand covert nuclear weapons program activity in other countries. Now the threat comes more from the diversion of materials from foreign civilian nuclear power programs to weapons-oriented activities. A vital nuclear industry in the U.S. is a factor in its national security.

The rising demand for nuclear power globally will be driven by increasing demand for electricity and concerns about the environmental consequences of fossil fuel use. Most global economic and climate models show electricity production growing by factors of three to six, regardless of emission constraints. Absent these constraints, the share of nuclear power would stay relatively constant at around 11%, but under emission constraints, nuclear generation would increase its share to about 17% (see Figure 3, page 9). As growing concern for the climate drives even natural gas out of the electricity portfolio, nuclear will be a critical partner to renewable energy and to carbon capture and sequestration as a carbon-free source of electricity. None of these is likely to supply, on its own, sufficient electricity to meet any reasonable level of global electricity demand.

One Path to a Robust Domestic Nuclear Power Industry

Although global electricity demands are growing, domestic demand is flattening. That trend, along with the high capital requirements of gigawatt-scale nuclear power reactors argue for a new approach to nuclear energy generation—namely, small modular reactors (SMRs). This study looks at the deployment of SMRs with standard designs as the next generation of nuclear power. Widely supported but not yet implemented, SMRs could provide a path to a robust domestic nuclear power industry.

SMRs in general are fission power plants that produce 10s to 100s of megawatts of electricity (MWe), compared to today's large pressurized-water reactors, which can generate more than 1,000 MWe. The small size enables many identical units of a standardized design to be manufactured in a factory and assembled on site. Such designs should be cheaper as well as safer, thanks to such features as lower fuel inventory, passive safety designs, and simpler containment structures. There is an active research effort to develop various designs.
The deployment of SMR technology in eight to ten years is a real possibility. One example is a conventionally fueled, light-water SMR that has been designed by NuScale Power to be "walk away" safe. It is currently undergoing licensing at the U.S. Nuclear Regulatory Commission (NRC) through a cost-shared program with the Department of Energy (DOE). The NuScale Power design consists of 50 MWe modules typically arranged as a "12 pack" in a 600 MWe plant.

Absent federal government intervention, the number of new starts for nuclear plants and reactors, both large and small, is projected to be so low that the industry will struggle to survive and eventually disappear. This is particularly true with SMRs where first-of-a-kind costs are prohibitive. Largely because natural gas is now so inexpensive in the U.S., gas generation facilities are less costly and companies can recover capital investments more quickly.

Absent federal government intervention, the number of new starts for nuclear plants will be so low that the industry will struggle to survive and eventually disappear.

Nonproliferation benefits and the social cost of carbon emissions do not objectively appear in the economic decision regarding natural gas versus nuclear, so the decision to select gas is rational but not necessarily best from a larger national security perspective.

The current lifetime cost differential between nuclear reactors and natural gas plants is higher than current production tax credits (PTCs) for other forms of energy or modeled levels of carbon taxes. For example, NuScale Power estimates that its levelized cost of electricity (LCOE)—the net present value of building and operating a power plant over the lifetime of its operation—will be approximately 8.5 cents per kilowatt-hour (kWh), or roughly 3 cents more than a combined cycle natural gas-fueled plant. The government currently offers PTCs for nuclear power of 1.8 cents per kWh for the first 6,000 MWe of new nuclear power but even that incentive only applies to reactors placed into service before December 2020. A renewal of those PTCs might be one way to improve the outlook for nuclear power. Costs should also reflect the added expense of required "peaker plants," which are necessary to supplement power when renewable plants are offline.

In addition to government subsidies, two further urgent actions may be considered. The federal government could begin the process of establishing a fuel leasing regime in which all fuel provided to emerging members of the nuclear power community should be returned to the U.S. for disposition after use. Those emerging nuclear customers include countries currently without infrastructure for nuclear power production, countries with small programs, or developing countries choosing nuclear power. Such a leasing program could be a model for other governments that build and fuel nuclear reactors around the world, and the amount of returned spent fuel would be small compared with domestic obligations.

Second, the U.S. needs to take tangible steps towards developing both consolidated storage and permanent geologic repositories for spent nuclear fuel and high-level waste, as well as create permitting, licensing, and inspection protocols for interim storage facilities. The government has statutory and contractual obligations to receive spent nuclear fuel from U.S. utilities. An application has been submitted for a geologic repository at the Yucca Mountain site in Nevada but has not been acted on.

The deployment of the Waste Isolation Pilot Plant (WIPP) in New Mexico for transuranic waste from the U.S. nuclear weapons program suggests that affordable and publicly acceptable geologic repositories can be developed and deployed in the U.S. The safety record of U.S. nuclear generation facilities and their productivity has been continuously improving for several decades, with online rates in excess of 90 percent. Experts from the U.S. nuclear industry have been leaders in the development of safety protocols for the global nuclear community. As the community of countries operating nuclear reactors grows, the U.S. should continue endorsing the Institute of Nuclear Power Operations (INPO) and World Association of Nuclear Operators (WANO) as critical and effective components of a safe and reliable global nuclear energy industry.

The U.S. has the programs, the available technology, and the institutional capital that can help address the existential national problems of nuclear weapons proliferation and mitigation of greenhouse gas (GHG) emissions.

With the following steps adopted by the federal government, the U.S. nuclear industry could regain full vitality and continue to lead in both nuclear technology and nuclear nonproliferation:

- Revitalize the domestic civil nuclear energy program.
- Support and expedite the deployment of SMRs, while also encouraging the development of next generation technologies.
- Establish the basis for a nuclear fuel leasing program for non-weapons states, and take tangible steps toward establishing permanent geologic storage for high-level civilian waste.
- Support and strengthen existing national and international programs for safe and effective operation of nuclear facilities.

Chapter 1—Urgency

On the Wrong Path

The declining prospects for the civilian nuclear industry in the U.S., if not reversed, could endanger the nation's future energy capabilities, environmental progress, and national security. Why should urgent action be taken and what specific steps are appropriate?

The U.S. has led the world in the development and introduction of civilian nuclear power. It maintains the largest domestic fleet of nuclear power plants, at approximately 100 gigawatts (GWe) of generating capacity.[1] Unfortunately, overall growth in U.S. electricity generation from nuclear power has stopped in the last ten years, as shown in Figure 1. In October 2016, the first new U.S. reactor in twenty years was completed and entered commercial operation. That plant was the Watts Bar Unit 2 in Tennessee, whose construction had been halted in the mid-1980s and then restarted in 2007.[2, 3] Of the four new reactors under construction in the U.S., two projects have been abandoned,[4] and the future of the other two reactors is uncertain.[5] Beyond these reactors, all plans for additional nuclear power plants in the U.S. are on hold.

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[1] International Institute for Applied Systems Analysis [IIASA], 2012. *Global Energy Assessment—Toward a Sustainable Future, Cambridge, UK, Cambridge University Press*, p. 1079.

[2] Tennessee Valley Authority, 2016. "Watts Bar Unit 2 Complete and Commercial," Press release, October 19, 2016, available at https://www.tva.com/Newsroom/Watts-Bar-2-Project (last accessed August 2017).

[3] International Atomic Energy Agency, 2017. "Power Reactor Information System: Watts Bar 2," available at https://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=700 (last accessed August 2017).

[4] S. Mufson, "S.C. Utilities Halt Work on New Nuclear Reactors, Dimming the Prospects for a Nuclear Energy Revival," Washington Post, July 31, 2017, available at https://www.washingtonpost.com/business/economy/sc-utilities-halt-work-on-new-nuclear-reactors-dimming-the-prospects-for-a-nuclear-energy-revival/2017/07/31/5c8ec4a0-7614-11e7-8f39-eeb7d3a2d304_story.html?utm_term=.52842ce437e9 (last accessed August 2017).

[5] World Nuclear Association [WNA], 2017. "Nuclear Power in the USA," available at http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx.

Annual U.S. Electricity Generation from Nuclear Power

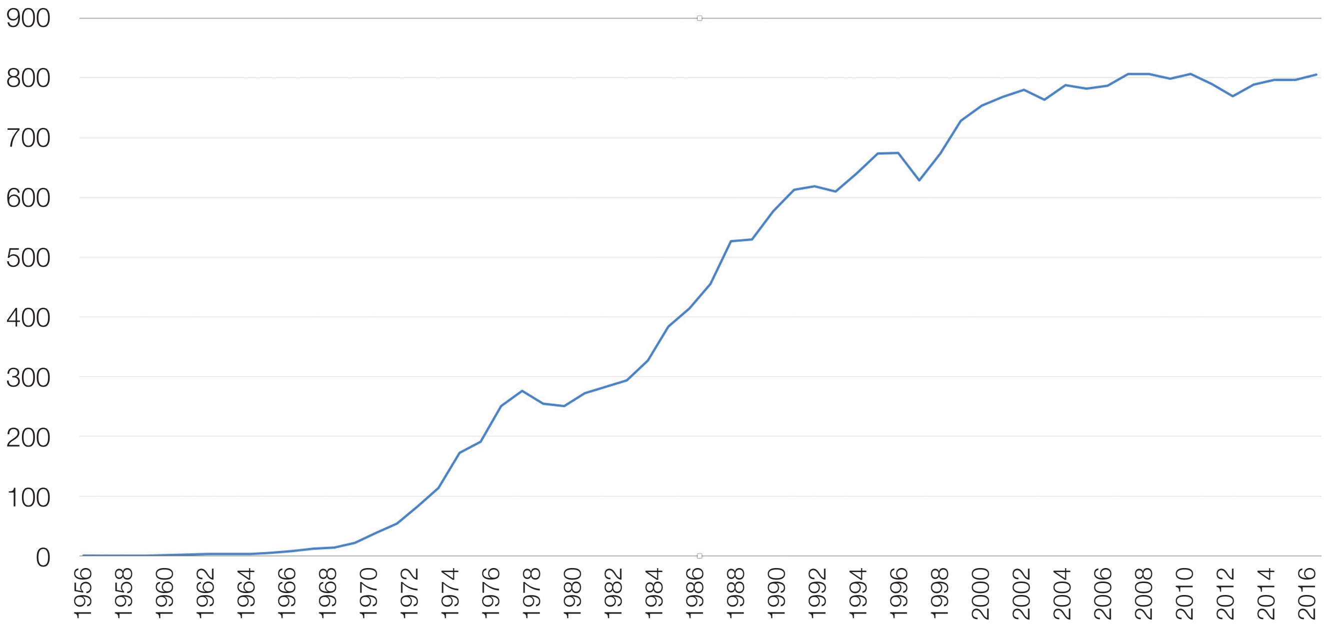

Figure 1. Annual U.S. Electricity Generation from Nuclear Power, 1956-2016.
Source: EIA Monthly Energy Review*, Table 7.2b.*

Older nuclear power plants have begun to be shut down, due to a variety of factors (see text box below).

Challenges for the Existing Nuclear Power Fleet

Market Factors Early retirement of reactors is caused more by inexpensive alternatives rather than by high operating costs. Wholesale electricity prices have fallen substantially over the last several years due to reduced demand, a continued abundance of low-cost shale gas, and competition from renewable energy sources whose prices have been reduced by subsidies. These market factors are unlikely to change significantly in the near term. Even cost-cutting measures implemented by the nuclear industry to reduce operating cash flow losses are unlikely to prevent early retirements for a significant number of plants in deregulated market areas.[6]

Competition with Natural Gas Natural gas plays a significant and rapidly expanding role in the U.S. market for electricity production. A recent assessment[7] by the Nuclear Energy Institute (NEI) points to several factors that hinder nuclear energy. The current market fails to recognize the importance of fuel diversity, base load capacity, and system resilience.

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6 "Economic and Market Challenges Facing the U.S. Nuclear Commercial Fleet." Energy Systems Strategic Assessment Institute, INL/EXT-16-39951, September 2016.

7 "The Future of Nuclear for the U.S.," presentation by Maria Korsnick, President and CEO, Nuclear Energy Institute, August 9, 2017.

Federal Programs Wind energy receives production tax credits (PTC) of 2.3 cents per kilowatt hour (kWh) for the first ten years of operation, approximately half of the typical wind turbine lifetime. Lower PTCs for nuclear power are now available for a shorter period of time but only for new plants completed before 2020, and a much shorter fraction of a nuclear reactor lifetime of sixty years. Congress may extend the nuclear PTC,[8] which will help offset costs of new facilities, but not the existing fleet, for which the federal government has few options.

State Programs At the state level, there is focus on the advantages of nuclear energy in addressing climate change and in providing operational reliability. The states of Illinois and New York have created programs to promote clean energy by subsidizing continued operation of nuclear power plants that would otherwise shut down for economic reasons. Similar programs are being considered by other states.[9] Although several states have considered actions to preserve nuclear power to provide resiliency to grids or as a hedge against future carbon emission regulations, their success is uncertain.

Decommissioning Nuclear power facilities cannot be idled awaiting changes in market conditions. In fact, current regulations and financial constraints encourage the timely decommissioning of nuclear facilities, making closure decisions irreversible, and further diminishing the prospect of maintaining existing plants.

The NEI assessment predicts that, given current market trends, it is likely that within the next ten years there will be a drop in nuclear energy production of from 20 to 30 percent due to plant closings.

Additional References

1. "Economic and Market Challenges Facing the U.S. Nuclear Commercial Fleet," Energy Systems Strategic Assessment Institute, INL/EXT-16-39951, September 2016.
2. "The Future of Nuclear for the U.S.," presentation by Maria Korsnick, President and CEO, Nuclear Energy Institute, August 9, 2017.
3. "Turns Out Wind and Solar Have a Secret Friend: Natural Gas," Chris Mooney, *Washington Post*, August 11, 2016.
4. Executive Office of the President, Office of Management and Budget, Statement of Administration Policy, H.R. 1551—Modifying Advanced Nuclear Power Tax Credit, June 20, 2017.
5. "An America First Energy Plan," https://www.whitehouse.gov/america-first-energy.
6. "The Trump Administration Just Disbanded a Federal Advisory Committee on Climate Change," *Washington Post*, August 20, 2017.

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[8] A proposal is pending in Congress to extend the tax credit beyond this date. For description of the existing tax credit and the proposed change, see Joint Committee on Taxation, "Description of H.R. 1551, a Bill to Amend the Internal Revenue Code of 1986 to Modify the Credit for Production from Advanced Nuclear Power Facilities (JCX-28-17)," June 14, 2017, available at https://www.jct.gov/publications.html?func=startdown&id=5001.

[9] "Economic and Market Challenges Facing the U.S. Nuclear Commercial Fleet," Energy Systems Strategic Assessment Institute, INL/EXT-16-39951, September 2016.

A "nuclear cliff" is emerging as many currently operating plants in the U.S. near the end of their existing operating licenses starting around 2030, as shown in Figure 2. The majority of the current nuclear fleet are licensed for sixty years (forty years initial license plus a first twenty year extension). The industry and the U.S. Nuclear Regulatory Commission (NRC) are making plans for a subsequent license renewal (SLR) program under which existing plants could apply to extend operating licenses for an additional twenty years. The Energy Information Administration (EIA) of the U.S. Department of Energy (DOE) projects in its *Annual Energy Outlook 2017* that some of these reactors will have their licenses extended, but this outcome is not assured.

Annual U.S. Electricity Generation from Nuclear Power

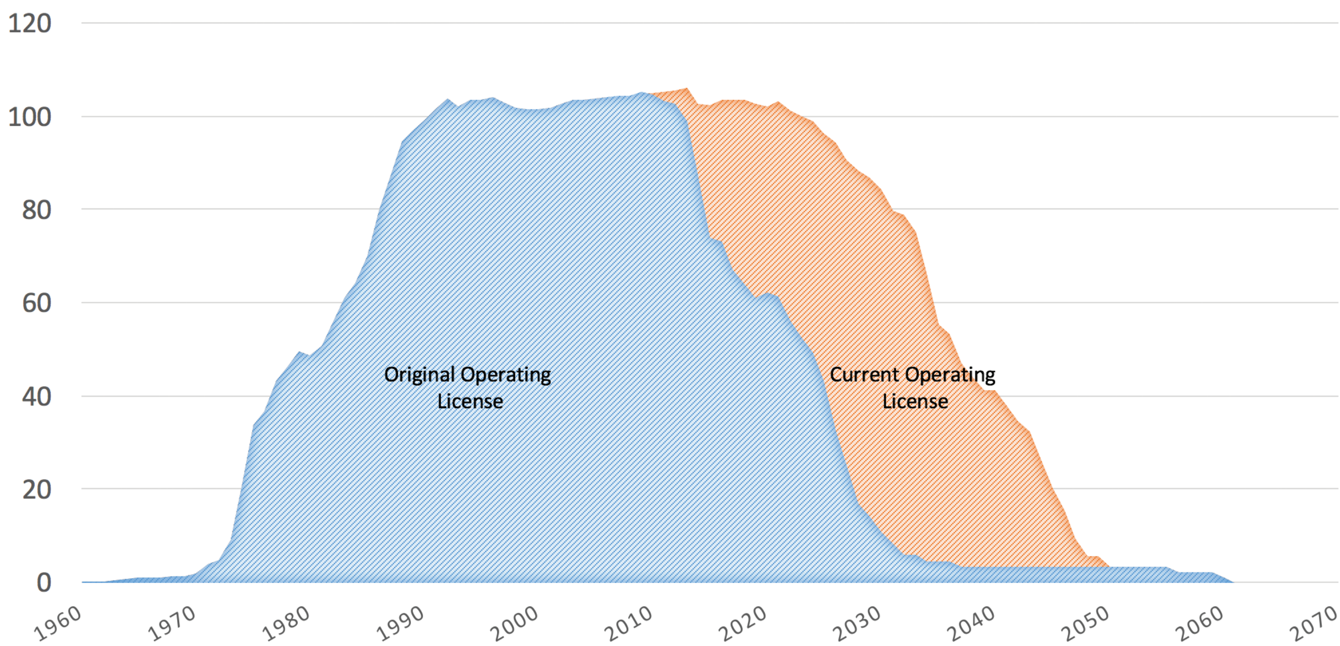

Figure 2. Currently Licensed Lifetime of U.S. Nuclear Capacity.
Source: Oak Ridge National Laboratory.

The twenty year hiatus in building nuclear power plants has resulted in an overall loss of expertise in constructing such facilities and perhaps contributed to recent new projects being behind schedule and over budget. These schedule delays and cost overruns illustrate the lack of an adequate U.S. supply chain for nuclear power.[10] The problem is about to get worse. The recent bankruptcy filing by Westinghouse, caused by its problems in managing the construction of recent reactor projects, means that the U.S. has lost its last major domestic supplier of commercial nuclear power plant technology. It also signals a further deterioration of the supply chain for civilian nuclear power.

[10] T. Hals and E. Fitter, "How two cutting edge U.S. nuclear projects bankrupted Westinghouse," Reuters, May 2, 2017, available at https://www.reuters.com/article/us-toshiba-accounting-westinghouse-nucle-idUSKBN17Y0CQ.

National Security Implications

As has been noted by numerous sources, most recently in a report by *The Energy Futures Initiative*,[11] U.S. influence on nuclear nonproliferation efforts hinges on its leadership in commercial nuclear technology, particularly nuclear power. Grave national security consequences are at stake with the looming loss of U.S. leadership in the civilian nuclear power market. In markets for nuclear power, the adage that the "point of sale is the point of influence" is highly relevant. U.S. commercial nuclear deals with international customers must satisfy the provisions of section 123 of the Atomic Energy Act, which translate U.S. nonproliferation objectives into conditions that are required for any U.S. export of nuclear technology. Such "123 Agreements" can shape decisions of nuclear client countries over a significant period of time.[12] Not only do these commercial transactions provide a mechanism for meeting U.S. nonproliferation and safety goals, but the relationships of the U.S. to its client states also give the U.S. significant persuasive power in the multilateral forums regarding the global "nuclear governance" regime.[13] The loss of U.S. leadership in nuclear power and the shift to nontraditional supplier nations risks significant erosion of the nonproliferation and safety norms that comprise the current nuclear governance regime.

The global nuclear supplier landscape is in rapid transition. Like the U.S., other traditional suppliers such as France and Japan have seen a diminishing demand for nuclear technology and are at risk of becoming minor international players. Now, Russia, South Korea, and soon China are aggressively marketing their nuclear technology and services. If current projections hold, these countries are positioned to capture greater market share in the future and to supplant former major suppliers in the race to address escalating global energy demands.

The major nuclear states of the western world, especially the U.S., have historically played a significant role in the development of the existing regulatory regimes. Moreover, although the

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[11] The publication of The U.S. Nuclear Energy Enterprise: A Key National Security Enabler: A Special Report by the Energy Futures Initiative is available at https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5992f7e0bf629ad8f9d575ec/1502803938248/EFI+Nuclear+Report+FINAL+08.2017.pdf

[12] Prior to any U.S. engagement in significant civilian nuclear cooperation with other states, a framework agreement that meets specific requirements under Section 123 of the Atomic Energy Act (AEA) must be concluded and reviewed under special parliamentary procedures by Congress. Significant nuclear cooperation includes: "the export of reactors, critical parts of reactors, and reactor fuel." The AEA includes nine specific nonproliferation criteria that must be met, export control licensing procedures, and the criteria for terminating cooperation. See Paul Kerr and Mary Beth D. Nikitin, "Nuclear Cooperation with Other Countries: A Primer," Congressional Research Service, December 27, 2016.

[13] "Nuclear governance" is relatively new in the vernacular and reflects more holistic thinking about the various elements related to the safe and secure handling of nuclear materials and operations at nuclear facilities. The nuclear "governance regime" is intended to convey the treaty-based obligations embedded in the Nuclear Nonproliferation Treaty (NPT), the role of the International Atomic Energy Agency (IAEA) and its corresponding bilateral Safeguards Agreements with NPT Member States as well as the IAEA's Information Circulars that inform best practices in implementation. The governance regime also involves many international conventions related to the secure storage or transport of nuclear materials, such as the Convention on the Physical Protection of Nuclear Materials (CPPN) and the International Convention for the Suppression of Acts of Nuclear Terrorism (ICSANT), and several operational best practices and standards emanating from the U.S.-based Institute of Nuclear Power Operators (INPO), the World Association of Nuclear Operators (WANO), and the World Institute for Nuclear Security (WINS).

U.S. civilian nuclear enterprise has deep expertise in nonproliferation and nuclear safety, these emerging suppliers have not yet demonstrated a commitment to carrying forward these long-standing international norms. This raises serious questions about how effectively the existing nuclear governance regime will be implemented in the future and where any impetus for future improvements might originate.[14] If U.S. involvement as a supplier of civilian nuclear energy disappears, the ability to enforce adherence or lead efforts at improvement in nuclear governance will be significantly reduced.

U.S. Leadership in Shaping a Nuclear Security Regime

Leadership in nuclear nonproliferation by the U.S. enabled it to exercise significant global influence in the past, as was exemplified by the recent Nuclear Security Summit process. At that summit, held in 2010, the U.S. hosted a gathering of forty-seven heads of state and three international organizations to endorse a four year goal of securing all of the world's vulnerable nuclear materials. Over the course of six years, the summit process collected unilateral and multilateral commitments on a broad range of measures related to nuclear security, including commitments to United Nations Conventions, additional voluntary contributions to the International Atomic Energy Agency's Nuclear Security Fund, promulgation and passage of implementing legislation, and establishment of regional and national "Centers of Excellence" for nuclear security training.[15] This process continued with additional summits convened in South Korea (2012) and in The Netherlands (2014), and culminated in a final meeting in Washington, D.C. in 2016. Expert observers of the process and major advocates for a new "regime" focused on nuclear security, emphasized that this summit process had been successful in shifting the international discourse to encompass security, along with the traditional elements of safeguards and safety. Although other countries have hosted summit gatherings, there is little doubt that only the U.S. could have successfully orchestrated and shepherded such a process.[16]

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[14] For example, not only will China become the largest nuclear operator at some point between 2020 and 2030, according to currently announced plans, but it is eyeing exports and new nuclear power plant builds in emerging economy nations and the West. See "Nuclear Power in China, World Nuclear Association, 2017, available at http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx. Russia is offering a build, own, and operate model that provides cradle-to-grave financing, operational expertise, fuel, decommissioning services, and spent fuel disposal. South Korea is supplying the four reactors being built in the United Arab Emirates and will manage their operation. These developments are unique; the traditional model required that recipient nations indigenously operate their plants. This new model highlights questions regarding the adequacy of the human and technical infrastructure in emergent nuclear power states to safely and securely sustain operations and prevent misuse. See "Evolving Nuclear Governance for a New Era: Policy Memo and Recommendations," *Global Nexus Initiative* (April 2017), p. 2.

[15] Ken Luongo and Michelle Cann, "Nuclear Security: Seoul, The Netherlands and Beyond," U.S.-Korea Institute at SAIS, 2013, p. 17.

[16] Elizabeth Turpen, "The Nuclear Security Summit Experiment: Has it Been a Catalyst for Action?" in International Cooperation and WMD Nonproliferation, Jeffrey W. Knopf ed. (University of Georgia Press, 2016), pp. 182-204.

With an exit from the nuclear supplier market, the U.S. would be ceding its position in the creation and uses of nuclear technologies. Our departure from the cutting edge of nuclear science would have implications beyond the more diffuse application of our leadership in the multilateral forums on nuclear governance. Indeed, the atrophying of U.S. participation in new nuclear technology development and its applications would have much more direct and dire impacts on its ability to adequately address its national security needs. As with any dual-use technology, policy decisions of major consequence frequently require deep scientific knowledge and strong analytical capabilities to render sound judgment on others' capabilities and to test assumptions accurately. The U.S. must maintain robust nuclear capabilities to anticipate and respond to the dangers associated with other countries' nuclear activities. This is not a hypothetical concern. It has proven true with the recent negotiation and conclusion of the Joint Comprehensive Plan of Action (JCPOA) with Iran as well as a detailed understanding of North Korea's program and its progress on development of nuclear weapons.

The use of nuclear power will continue to expand both in response to a global increase in electric power demand and a desire to mitigate emissions that lead to climate change. Without prompt and decisive action to arrest and reverse the loss of expertise that comes from being a major supplier of nuclear energy technology, U.S. global leadership in nuclear nonproliferation and core national security needs will be at risk.

Hanford: The Application of DOE Capabilities to Address National Security Needs

The U.S. capability in nuclear technologies has been critical to U.S. policies on proliferation. Hanford, in eastern Washington State, was one of the Manhattan Project sites responsible for the production of plutonium. As a result, Hanford had an extensive range of nuclear facilities, including fuel fabrication buildings, reactors, separation and conversion plants, waste storage tanks, and laboratories. From the very beginning of operations, the detection, measurement and monitoring of radioactive materials and effluents have been a high priority for quality control, worker safety, and environmental protection. Importantly the same radioactive measurement and monitoring capabilities at Hanford have been used to detect and monitor nuclear weapons production and testing worldwide. For example, in late 1949, a test and calibration of that capability was conducted when fuel was deliberately cooled for a shorter period than normal. The resulting high concentrations of short-lived elements were reprocessed (the so-called "green run") to confirm detection capability through air monitoring. Detection and analysis capabilities continue to be developed and refined, and they still play a vital role in international safeguards, including enhanced standards currently used by the International Atomic Energy Agency (IAEA). DOE capabilities at Hanford also played an essential role in informing U.S. participants during the negotiation of the JCPOA with Iran in 2015.

Iran: Deep Analytical Capabilities to Address Imminent Dangers

The critical importance of U.S. nuclear analytical capabilities is illustrated by the negotiations and continued verification of Iran's compliance with the terms of the JCPOA. The goal of the deal was to substantially increase the timeline for any breakout scenario[17] on the part of Iran, while allowing it to proceed with appropriate civilian nuclear activities. This required detailed understanding of the enrichment facilities and civilian reactors that comprise Iran's nuclear program as well as continuous feedback regarding specific terms in the deal to ensure they met negotiators' objectives. According to former Secretary of Energy Ernest Moniz, the deal is "based on science and deeply grounded in exhaustive technical analysis."[18] The scientific and technical teams at DOE, seven national laboratories, and two DOE nuclear sites were actively involved in analyzing options for the Iran agreement in near real time. Equally important, expertise in the nuclear fuel cycle, nuclear safeguards, security, and nuclear materials will be required to ensure that Iran is meeting its key commitments under the conditions set forth in the agreement.[19]

Climate Security Concerns

Losing the domestic option for future civilian nuclear power would also have important climate security consequences. Energy-related emissions of CO_2 are a key part of overall anthropogenic generation of greenhouse gases (GHG), which are now the highest in history and which are believed to be a dominant cause of observed global warming since the mid-20th century.[20] Emission of GHGs at or above current levels will likely cause further warming, ocean acidification, and potential long-lasting changes in all components of the Earth's climate system. These changes will increase the likelihood of severe, pervasive, and irreversible impacts to people and ecosystems.[21]

By the middle of this century, there will be a rigorous international push to achieve near-zero GHG emissions from electricity generation. The goal will be to reduce the release of CO_2 to the atmosphere to near zero by the end of the century. In addition to efficiency improvements, there are several possible options for electricity with near-zero GHG emissions, including renewable energy sources such as wind and solar, fossil sources with carbon capture and storage (CCS), and nuclear power. The international community will pursue all these strategies as well as others that may arise.

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[17] A breakout scenario is a rapid buildup from strictly a nuclear energy program to one that includes a weapons program.

[18] Secretary Moniz's Testimony before the Senate Foreign Relations Committee on the Iran Deal (July 23, 2015).

[19] See "Statement from Secretary Moniz on Implementation Day of the Joint Comprehensive Plan of Action" (January 16, 2016). News release, Energy.gov, January 16, 2016: https://energy.gov/articles/Implementation-Day-Moniz-Statement.

[20] Intergovernmental Panel on Climate Change, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland [IPCC SYN], 2, 4.

[21] IPCC SYN, 8.

As the use of nuclear power grows globally in response to this challenge, the U.S. has an important choice to make. If it opts to allow the domestic nuclear power industry to become insignificant so that other nations turn to non-U.S. vendors, the U.S. will no longer have the same ability it has used to influence the safety and proliferation resistance of nuclear systems. In meeting its own energy needs, the U.S. might choose to rely on non-nuclear, near-zero carbon electricity sources to achieve near-zero domestic emissions. Or the U.S. could join the rest of the nations to purchase nuclear reactors from countries such as Russia, China, South Korea, and India. A significant domestic nuclear industry would provide the U.S. with another low carbon electricity option and also help the U.S. to pursue its nonproliferation agenda through interactions with other nations as they acquire nuclear power capability.

International efforts under the United Nations Framework Convention on Climate Change have focused on global strategies to combat the human causes of climate change and to adapt to the effects of climate change that can no longer be avoided. In 2015, world leaders adopted the Paris Agreement, which committed the international community to strengthen its response to climate change by keeping the global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.[22] Every model for achieving this target involves expanding global nuclear power as part of a portfolio of low- and zero-carbon energy technologies.[23] As shown in Figure 3, the International Energy Agency (IEA) has analyzed an energy mix in 2050 that would lead to a 6 degree Celsius warming by 2100 (the 6DS scenario, corresponding to continuation of existing energy policies) and the energy mix in 2050 that would be required to have a 50 percent chance of not exceeding a 2 degree warming by 2100 (the 2DS scenario).

Electricity Production by Technology in the 6DS and 2DS

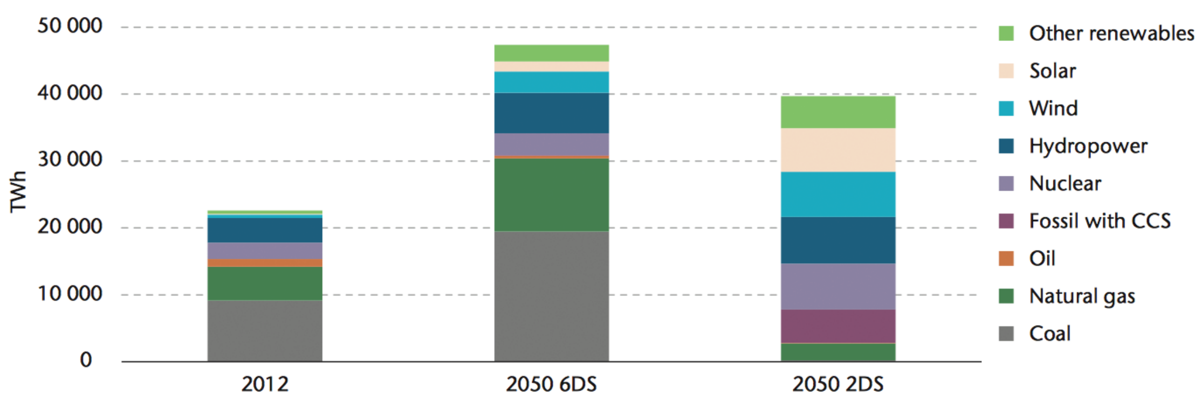

Figure 3. IEA Technology Mix for Decarbonization of the Power Sector by 2050.
Source: IEA, Energy Technology Perspectives: Technology Roadmap: Nuclear Energy, 2015 Edition.

[22] United Nations Framework Convention on Climate Change: The Paris Agreement, available at http://unfccc.int/paris_agreement/items/9485.php.

[23] The one notable study claiming to model the achievement of future climate targets solely with renewable energy technologies has been shown to contain significant flaws. See C.T.M. Clack, et al. (2017), "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar," Proc. Natl. Acad. Sci. USA 114:6722-6727. doi: 10.1073/pnas.1610381114.

Although renewable energy technologies make up most of the technologies in the energy mix in 2050 under the 2DS scenario, nuclear power increases from its current global generation share of 11 percent to 17 percent in 2050. Although this seems like a modest increase, it is equivalent to an increase of two and a half times the amount of global nuclear power capacity (from 396 GWe in 2014 to 930 GWe in 2050).

Although the increase in renewable and natural gas-fired generation and the accompanying decrease in coal-fired generation have lowered U.S. emissions of CO_2 over the last eight years,[24] to meet the targets in the 2DS scenario, the U.S. will have to increase its efforts to transition away from energy sources that emit GHGs. A study by the International Institute for Applied Systems Analysis (IIASA) of all the national commitments that have been submitted to date to implement the Paris Agreement, termed Nationally Determined Contributions, or NDCs concludes that:

> in order to keep warming to below 2°C, countries should either increase the stringency of their NDCs by 2030 or consider scaling up their ambition after 2030 by a factor of 4 to 25. If the ambition of NDCs is not further increased by 2030, the study finds no pathways for returning warming to 1.5°C by the end of the century.[25]

Revitalizing the nuclear option for electricity generation in the U.S. can play an important role in achieving greater ambition for national CO_2 reduction in electricity generation. Because power plants typically have a projected lifetime of several decades, it is important to have a robust suite of carbon-free generation options that can be built over the next two decades. Plants built before 2050 will be some of the plants in use in the last half of the century when mitigation constraints are likely to be more urgent. This is true internationally, and particularly in developing countries, whose electricity consumption is projected to increase over the next few decades.

Carbon capture and storage technologies are in early stages of deployment. They continue to be researched as an option for the utilization of fossil fuels with zero emissions to the atmosphere, but many aspects of these technologies remain unproven at scale. The unknowns include the efficiency of capture and the ability to achieve long-term sequestration without leakage to the atmosphere,[26] and the impact that increased seismic events might have on the widespread application of this technology.[27]

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[24] R.M. Simon and D.J. Hayes (2017), "America's clean energy success, by the numbers," Center for American Progress, available at https://www.americanprogress.org/issues/green/reports/2017/06/29/435281/americas-clean-energy-success-numbers/.

[25] IIASA (2017), "Ambiguous pledges leave large uncertainty under Paris climate agreement," available at http://www.iiasa.ac.at/web/home/about/news/170606-INDC.html.

[26] G. Shaffer, 2010, "Long-term effectiveness and consequences of carbon dioxide sequestration," Nature Geoscience 3:464-467, doi:10.1038/ngeo896.

[27] National Academies of Sciences, Engineering, and Medicine, Committee on Induced Seismicity Potential in Energy Technologies (2013), Induced Seismicity Potential in Energy Technologies, 12, available at https://www.nap.edu/download/13355#.

In summary, there is an urgent need for a suite of near-zero-carbon electricity generation technologies to meet the climate challenges of this century. U.S.-led clean energy technology development and deployment has been important to date and will be needed in the future. There remains an urgent need to ensure that nuclear power is available to help address our environmental and security commitments.

Modeling the Growth of the Global Nuclear Sector

One way to analyze the importance of a nuclear sector is through an "integrated assessment model," which is generally a global economy model combined with an earth system model. The two most technology-rich models in the U.S. have been developed by teams at the Pacific Northwest National Laboratory/University of Maryland (PNNL) and at the Massachusetts Institute of Technology (MIT).

These two models both use a reference case with substantial global growth in nuclear power. Each model also shows much more growth in nuclear power under climate constraints. In the PNNL model,[28] the size of the nuclear power sector in 2100 under a strict emission limit is twice as large as under a reference case with no CO_2 emission constraints. If the same emission-limited scenario is run without a carbon capture and sequestration option, the nuclear energy share doubles again. In the MIT model,[29] under a strict climate constraint, the model indicates that nuclear power provides about 85 percent of the global electricity supply by 2100.

Worldwide, integrated assessment models are generally not as optimistic about nuclear power as are technology-rich U.S. models, and the heterogeneity among model results is significant. Nevertheless, the amount of global nuclear energy generated increases from 10 exajoules (EJ) in 2010 to a modeled range of 0-66 EJ with a median of 39 EJ in 2100 without a climate constraint, and to a modeled range of 11-214 EJ (median 67 EJ) with a climate constraint (450 ppm scenario). The share of nuclear electricity as a fraction of total electricity drops slightly from 11% in 2010 to range 0-25% (median 9%) in 2100 with no climate constraint but increases to range 2-38% (median 17%) in 2100 under the climate constraint.[30]

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[28] Joint Global Change Research Institute (PNNL and U. Maryland), The Challenges and Potential of Nuclear Energy for Addressing Climate Change, 2007, (Kim, Edmonds).

[29] MIT Joint Program on the Science and Policy of Global Change, 2016 Food, Water, Energy & Climate Outlook.

[30] Kim SH, K Wada, A Kurosawa, and M Roberts. 2014. "Nuclear Energy Response in the EMF27 Study." Climatic Change 123(3-4):443-460. doi:10.1007/s10584-014-1098-z.

Summary

- The domestic civilian nuclear power program is in decline and likely to be unsustainable within a few decades barring a significant, focused effort to reverse this trend.
- Individual sales of reactors enable the promotion of nonproliferation and safety goals to the nation acquiring the reactor. As a whole, sales provide U.S. influence in international forums to improve the global “nuclear governance” regime. Other nuclear suppliers are likely to have less interest and expertise in nonproliferation and safety.
- With the loss of a domestic industry, the nuclear expertise at DOE national laboratories, universities, and many other institutions will diminish, with a resulting decrease in the ability of the U.S. to accurately assess and counter future proliferation challenges.
- Nuclear power is a proven near-zero carbon energy source that can be deployed at scale and becomes even more critical globally under limitations of the emission of CO_2 under climate change constraints.

Chapter 2—A Path Forward for the U.S. Domestic Nuclear Industry

The previous chapter discussed the role of the U.S. civilian nuclear industry in providing a source of carbon-free power and in supporting international nonproliferation efforts.

Unfortunately, because the U.S. nuclear industry has been in decline for an extended period, the options for revitalizing U.S. leadership are quite limited.

Current Efforts to Sustain Nuclear Power

A number of efforts are underway to maintain, or at least slow the loss of the current fleet of nuclear reactors. Both New York and Illinois have taken actions to subsidize nuclear generation, thereby preventing premature closures. In 2016, the State of Illinois passed a temporary tax subsidy of 1 cent per kilowatt hour (kWh), avoiding the shutdown of two of the state's nuclear power plants, Clinton and Quad Cities.[31] The bipartisan bill was based partly on a 2016 report by the Energy Systems Strategic Assessment Institute,[32] which analyzed economic gaps between nuclear and wind energy. New York has also initiated a subsidy for nuclear power as a "clean" option.[33] Similar actions have been considered in Ohio and Pennsylvania.

The DOE's Light Water Reactor Sustainability Program is developing technologies and other solutions to maintain the safe and economic operation of the existing fleet for as long as possible and practical.[34] The Nuclear Energy Institute's effort, called Delivering the Nuclear Promise, "strengthens the industry's commitment to excellence in safety and reliability, assures future viability through efficiency improvements, and drives regulatory and market changes so that nuclear energy facilities are fully recognized for their value."[35]

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[31] https://www.forbes.com/sites/jamesconca/2016/12/04/illinois-sees-the-light-retains-nuclear-power/#-7f8eef463e7b.

[32] https://gain.inl.gov/Shared%20Documents/Economics-Nuclear-Fleet.pdf.

[33] https://www.nytimes.com/2016/08/02/nyregion/new-york-state-aiding-nuclear-plants-with-millions-in-subsidies.html?mcubz=0.

[34] Idaho National Laboratory (2017), "Light Water Reactor Sustainability Program," available at https://lwrs.inl.gov/SitePages/Home.aspx.

[35] Nuclear Energy Institute (2017), "Delivering the Nuclear Promise," available at https://www.nei.org/Issues-Policy/Delivering-the-Nuclear-Promise.

In addition to attempts to preserve the fleet, the U.S. also has several facilities in various stages of design and construction, as noted in Chapter 1.

Neither the efforts to maintain the current fleet nor the completion of reactors under construction would be sufficient to preserve U.S. leadership in nuclear power generation.

A variety of advanced reactor concepts—known as Generation IV reactors—are being developed. Their key performance features, outlined in the box "Advanced Reactors" on page 22, will offer economic, safety, efficiency, and fuel handling advantages over even the most advanced of recent Generation III plants. But most will not be available until the early to mid-2030s.

The Need for Small Modular Reactors

SMRs may provide a transition to a future when the Generation IV reactors described are ready to be deployed. SMRs contain advances in the best Generation III designs and they are more economic to build and operate in the current fiscal climate of the U.S. electric industry. This is why we see SMR technology as the path forward.

These reactors are not simply smaller versions of previous reactors. SMRs are designed so that their key components could be manufactured and assembled in factories and then shipped to a plant site, as opposed to being built and assembled on the site. Consistent and replicable construction in a factory setting confers several important advantages that help avoid many of the cost overruns and other problems that have hindered past deployment. The cost of the specialized production equipment is allocated across multiple reactors of the same design constructed in a central facility. Proponents of SMRs suggest this process could lead to lower design costs, lower-cost quality control, and regulations that would be easier to apply in a consistent manner. The smaller size provides more siting and cooling options, as well as more flexibility to integrate with other sources that produce electricity at variable rates.

SMRs could be used for energy production other than electric generation, such as district heating. Existing large nuclear power plant designs are not well suited to the scale of the economies and grids of many developing nations.[36] Smaller, more flexible designs could be a part of the portfolio of carbon-free options.

SMRs are ready to be licensed and built now. Because they could be implemented in the near term, the construction of new SMRs could re-establish a domestic supply chain and also revitalize engineering capability and technical expertise. Intent to purchase and operate new SMRs would provide market confidence that could overcome the concerns with first-of-a-kind deployment. And finally, a successful ramp-up in SMR construction over the near term would lead to the development of more complex nuclear technologies in support of a growing and improving

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[36] IIASA, 2012, Global Energy Assessment—Toward a Sustainable Future, p. 1078.

nuclear industry. The deployment of SMRs would lower barriers for other advanced reactor technologies because the SMR approach could be used with other concepts, such as high temperature gas, sodium-cooled, and molten salt reactors.

In calling for an increase in SMR technology use, it should be made clear that this is not a call for research, as the technology exists and is already proven effective. This is a call to action for concrete steps that could result in deployment of the technology. Deployment is essential to facilitate licensing and establish a manufacturing base.

Because the focus is on deployment, the balance of this chapter will focus on one particular SMR design. Our examination of the field suggests that NuScale Power has the SMR technology that is closest to deployment. Proponents of other designs appear to be waiting for this leader to clear some of the key regulatory issues, as noted below.

NuScale Power SMR Characteristics

The NuScale Power SMR is a 50 MWe (160 MW thermal or MWt) integral pressurized light water reactor (LWR) that uses natural circulation of the primary coolant for both regular operation and shutdown modes. A design certification application for this reactor has been submitted to the NRC.

NuScale Power's SMR is based on LWR technology and is similar to the current fleet of larger reactors. The use of this technology makes the design ready for licensing and construction because it takes advantage of decades of regulatory and engineering experience. The goals of this reactor design illustrate the advantages of SMR technology. It has a lower initial capital investment than today's larger reactors. The small volume pressure containment vessel contributes significantly to the large safety margins and overall resilience of the plant design.

The simplicity and robustness of the modular design allows for an increased level of automation in the control and operation of the modules. This would enable the entire plant to be operated from a single control room.

Its compact size allows off-site fabrication and load flexibility, and the possibility of being sited in a location that can't accommodate more traditional, larger reactors. NuScale Power also offers complete passive safety with no need for operator actions for an indefinite period—a feature commonly described as "walk-away safe." NuScale Power is scheduled to obtain a design certification from the NRC by the end of 2020 or early 2021. The NuScale Power technology offers a good case study for understanding both licensing and financing challenges.

SMR Regulatory and Technology Challenges

The deployment of SMR or other advanced reactor technologies would require overcoming a number of barriers. The regulatory system must recognize new approaches, such as a reduced emergency planning zone, fewer security guards, and a reduced operating staff that can monitor multiple reactors. A supply chain, consisting of qualified vendors, would have to be established. Each of these barriers is an important part of the overall cost of a system. Cost would likely stand as a major barrier to deployment. These challenges would need to be addressed to allow for a first-of-a-kind deployment with later transition to production models, sometimes called nth-of-a-kind.

SMR Cost Analysis

The EIA annually publishes costs of electricity production, and the costs are often presented as levelized cost of electricity (LCOE).[37] The LCOE divides the sum of all costs by the amount of electricity produced to arrive at an LCOE in dollars per megawatt hour (MWh) for future plants. Where applicable, tax incentives are subtracted from the costs used to determine the LCOE. LCOE is a convenient way to compare different generating technologies but does not predict which technology would be selected in specific circumstances due to many other considerations. An important caveat to these comparisons is that LCOEs assume that megawatt hours are fungible among different generation technologies.

The following table[38] (Figure 4) shows EIA's estimates for costs of several competing technologies for electricity production, along with two cost estimates provided by NuScale Power for their proposed SMR reactor.

The cost of advanced nuclear power is listed by the EIA at $96 per MWh or 9.6 cents per kWh. The vendor's estimate for the first-of-a-kind NuScale Power SMR is also $96 per MWh. The estimate for a production model is $85 per MWh; that estimate takes into account factors such as the expected savings as the construction becomes more efficient and as regulatory compliance becomes easier.

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[37] From: *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2017*, April 2017, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[38] Ibid. Data are extracted from Table 1a. Estimated LCOE (weighted average of regional values based on projected capacity additions) for new generation resources, plants entering service in 2022, p. 7.

U.S. Average LCOE (2016 $ per MWh) for Plants Entering Service in 2022

Technology	Total System LCOE	Levelized Tax Credit	Total LCOE Including Tax Credit
Advanced Nuclear	96		96
First-of-a-Kind Nuclear (NuScale)	96		96
Production Model* Nuclear (NuScale)	85		85
Gas Advanced Combined Cycle	54		54
Gas Conventional Combined Cycle	59		59
Gas Conventional Combustion Turbine	101		101
Gas Advanced Combustion Turbine	87		87
Geothermal	44	-3	41
Biomass	98		98
Wind—Onshore	56	-12	44
Solar PV	74	-16	58
Hydroelectric	64		64

*Also called nth-of-a-kind.

Figure 4. Levelized Costs of New Electricity Generation Resources: EIA Estimates and NuScale Power Comparison.
Sources: https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf and http://www.nuscalepower.com/smr-benefits/economical/operating-costs. The NuScale Power estimates are modified by NuScale Power to match EIA parameters, such as plants entered into service in 2022 and converted to 2016 dollars.

The EIA lists LCOE of natural gas advanced combined cycle reactor at $54 per MWh. This LCOE is based on scenarios of natural gas prices that rise in real terms to greater than $6 per million British thermal units (MMBtu) by 2050. The LCOE value scenario for natural gas prices that stays close to current prices would be in the low $40s per MWh.

With an estimate of the amount of CO_2 emitted per kWh from natural gas plants[39] and assumptions for the range of costs of nuclear and natural gas,[40] the value of a carbon tax that

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[39] A heat rate for new natural gas combined cycle plants of 7000 Btu/kWh (https://www.eia.gov/todayinenergy/detail.php?id=32572) shows average recent NGCC plants at about 7200 Btu/kWh) times a CO_2 emission factor of 53 kgCO2/MBtu gives about 0.37 tons CO_2 per MWh.

[40] Nuclear power low cost is $85 and mid/high is $96. Natural gas high cost is $54 and low cost is $42.

would make equal the LCOE cost for nuclear power and power from natural gas ranges from $85 per ton CO_2 to $145 per ton CO_2. Those values can be compared with EPA's published social cost of carbon, which is $79 per ton CO_2 and rising for 2050, depending on reference assumptions.[41] The $85 per ton CO_2 to $145 per ton CO_2 range can also be compared with a sample of global integrated assessment models that were run on a "medium-low" representative concentration pathway (RCP) 4.5 emissions scenario.[42] The ranges of modeled carbon taxes based on reference assumptions and the RCP 4.5 scenario ranged from $23 per ton CO_2 to $84 per ton CO_2 in 2050, and $128 per ton CO_2 to $680 per ton CO_2 in 2100.

A number of steps can be taken to help SMRs compete in the market, and many will involve some form of public–private partnership. The NEI, and other organizations focused on promoting nuclear power are proposing a range of actions by the U.S. government. Such actions include regulatory changes and licensing support; loan guarantees; market reforms; tax structure changes, such as production and investment tax credits; power purchase agreements; development of the supply chain; and research and development investment that reduces technology risk, lowers costs, and develops advanced manufacturing techniques. The support required by the federal government will be reduced as technology progresses from first-of-a-kind to routine deployment.

Uncertain Natural Gas Prices

The domestic price of natural gas has been quite variable and it is low relative to historical levels,[43] and compared with other countries.[44] The cost of producing electricity from natural gas is highly sensitive to the cost of fuel. Decisions to switch from nuclear or coal to natural gas could have at least two significant risks that utilities will have to manage—natural gas prices could increase significantly, and future efforts to limit GHG emissions could penalize natural gas.

Once regulatory and cost issues are addressed, the next critical item is initial deployment, which requires an established production path that has deployed enough reactors to stabilize price and to demonstrate the process of siting and commissioning the technology.

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41 Social cost based on the EPA Fact Sheet Social Cost Of Carbon, https://www.epa.gov/sites/production/files/2016-12/documents/social_cost_of_carbon_fact_sheet.pdf, $69 ($2007) converted to $2016.

42 Integrated assessment models were discussed in Chapter 1. The SSP Database (Shared Socioeconomic Pathways)—Version 1.1 is maintained by IIASA and is available at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about. The results of five international integrated assessment models reflect an analysis of the RCP 4.5, which is one of four Representative Concentration Pathways adopted by the IPCC for the Fifth Assessment Report. The 4.5 refers to watts/m^2 or about 550 ppm and is more likely than not to exceed 2 degrees centigrade warming.

43 EIA (2017), "Henry Hub Natural Gas Spot Price" (monthly averages from 1997-present), available at https://www.eia.gov/dnav/ng/hist/rngwhhdM.htm.

44 BP (2017), "Statistical Review: Natural Gas Prices," available at http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/natural-gas/natural-gas-prices.html.

Possible First Movers

Breaking through the first-of-a-kind barrier is an important step. The first mover establishes licensing of new technologies and learns many lessons that will guide followers. Two domestic utilities have started the process of constructing SMRs. Additionally, an industry group of customers and vendors, SMR Start,[45] is promoting the deployment and operation of advanced light water SMRs by the mid 2020s.

Utah Associated Municipal Power Systems (UAMPS) According to their website, UAMPS launched the Carbon Free Power Plant (CFPP) project in 2015, with thirty-two of its forty-six members electing to participate. The CFPP is in the first phase of investigating the feasibility of an SMR project using NuScale technology. The CFPP could consist of up to twelve 50 MWe reactors located at the Idaho National Laboratory (INL) near Idaho Falls. UAMPS chose the NuScale Power technology because it believes the design reduces complexity, improves safety, enhances operability, and reduces risks. The price is expected to be competitive among carbon-free energy options. The feasibility analysis includes engineering and regulatory activities to complete a site selection analysis to allow the project participants the necessary information to make a decision whether to proceed with the Construction and Operating License Application (COLA).
In February 2016, the DOE issued a Site Use Permit to UAMPS CFPP, granting it access to the INL site for the purposes of identifying potential locations for the NuScale power plant and, if suitable, the long-term use of a preferred site for such purposes. Initial licensing and investigative activities are underway with the expectation that the COLA will be completed in 2018.[46] UAMPS CFPP is projecting the first NuScale Power Module™ to achieve commercial operation in 2024, with the full 12-module plant doing so in 2025.

Tennesee Valley Authority (TVA) Early Site Permit (ESP) The TVA submitted an ESP in 2016 for the potential construction of SMR units. This schedule would allow the submission of a COLA in 2020. The TVA will decide when and if to proceed as the process unfolds.

The TVA Clinch River site is located near the Oak Ridge National Laboratory (ORNL) and the DOE's Y-12 National Security Complex in eastern Tennessee. Installing an SMR at this site could be a source of clean, reliable, secure power to this complex as well as to other customers. In May 2016, TVA submitted an ESP application to the NRC for the Clinch River site. The application is based on potential deployment of two or more SMR units. SMR designs being developed were used to create a "plant parameter envelope" for the analysis performed for the application.
TVA has not decided to proceed with the deployment of an SMR, but an ESP reduces future COLA risk by completing most of the siting and environmental matters associated with a specific site. The ESP application provides an evaluation of site safety, environmental conditions, and emergency preparedness. Additionally, the application addresses regulatory policy issues important to SMRs. For example, the TVA ESP application proposes an emergency planning zone

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[45] http://smrstart.org

[46] http://www.nuscalepower.com/our-technology/technology-validation/program-win/uamps.

of either the site boundary or two miles, depending upon the selected technology and subject to further evaluation at the COLA stage. The NRC completed the acceptance review of the TVA application in December 2016 and began the detailed technical review in January 2017.

Beyond First Movers

Once the initial deployment has taken place, the critical question is, will it lead to a sustainable capability? This, in turn, implies a stable long-term market that supports the industry. Three potential market drivers are suggested:

- Retirement of the current fleet of nuclear reactors.
- Retirement of the current fleet of coal-fired plants.
- Decarbonization of transportation and other sectors.

The first two drivers will require capacity replacement, even if electricity demand stays flat. The third driver will increase electricity demand, creating even more pressure on supply. This will present a market opportunity for new nuclear deployment, which could be led by the introduction of SMRs.

Nuclear Facility Retirements As discussed in Chapter 1, many U.S. nuclear reactors will reach the end of their operating licenses starting around 2030. Siting SMRs at the location of those retiring reactors would offer a number of advantages, including the presence of existing physical infrastructure, experience with nuclear power at the site, and prior resolution of regulatory issues.

Coal-fired Facility Retirements Many coal-fired plants are also slated to retire in the coming decades due to aging infrastructure and cost. As illustrated in Figure 5,[47] nearly 160 GWe of coal capacity (for plants greater than 300 MWe) is projected to be retired by 2040. These retirements open the door to replacement by nuclear reactors.

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[47] http://www.nuscalepower.com/images/our_technology/upgrading-americas-energy-system-nuscale-whitepaper.pdf. Retirement and decommissioning of a project is assumed to occur after sixty years of operation and only coal plants greater than 300MW in capacity are considered.

Coal Plants Over 300 MWe and Greater than 60 Years in Age

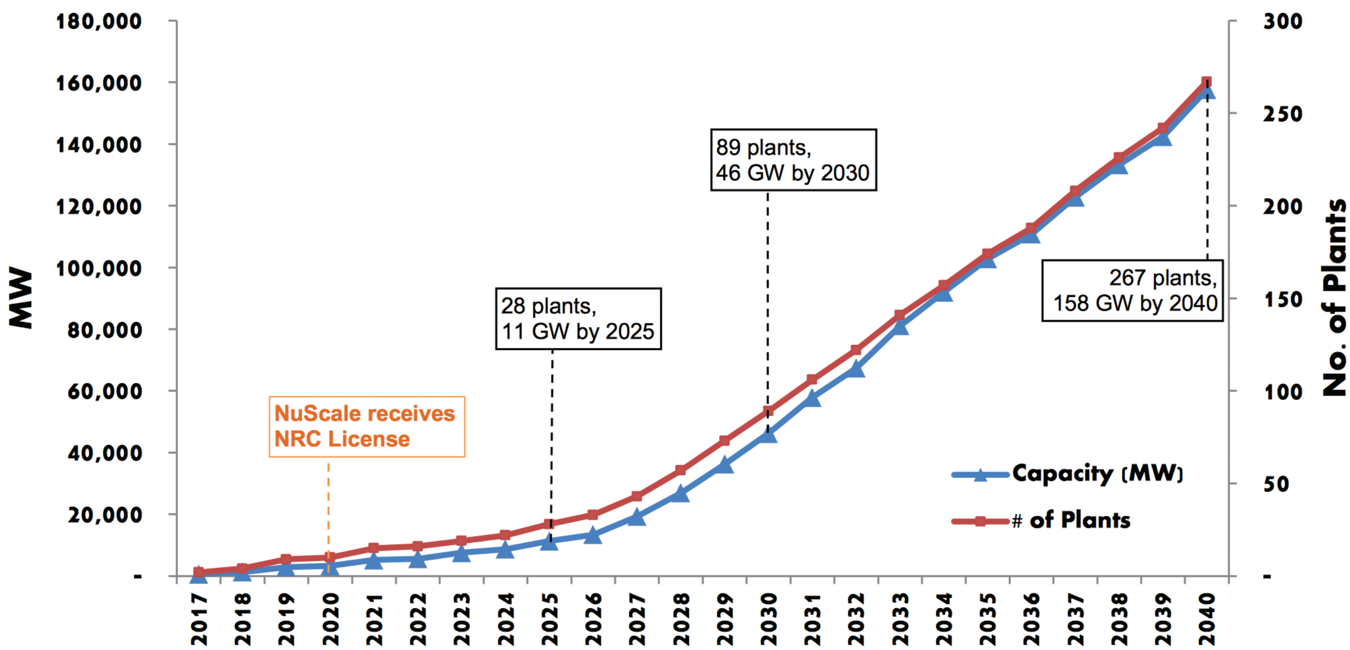

Figure 5. Cumulative Capacity and Number of Coal Power Plant Projects Expected to Retire in the U.S.
Source: GlobalData Analysis for NuScale Power.

Decarbonization The third driver for new nuclear demand will be the decarbonization of the electricity and other sectors not only in the U.S. but globally. Some of the decarbonization of the other sectors, such as transportation, may come through electrification with non-emitting sources. As stated in Chapter 1, long-term growth of nuclear power is a way of meeting this goal.

Challenges in the United States

The potential global move from first deployments to stable demand for nuclear power is hard to predict. Although in much of the world the government controls the nuclear power sector, this is not the case in the U.S. Commercial power producers provide practically all of the electricity from nuclear power; much of the country has a deregulated and competitive electricity supply market. Despite the lack of a federal implicit or explicit cost of carbon, some states are moving to establish or strengthen their carbon markets. One example is the Regional Greenhouse Gas Initiative (RGGI) in the Northeast. There remains a need for a *push* via public private–partnerships or other approaches to maintain nuclear capability. This will lead to a market *pull* as risks and costs are reduced.

Advanced Reactors

There are a number of innovative designs that potentially improve the economics, safety, and environmental impact of nuclear power. U.S. based companies are working on the design and development of these more advanced systems. The maturity of these designs varies among the different options, but most show deployment schedules that make them available in the early to mid 2030s.

Many of the advanced reactor designs are not based on light water as a coolant. These include high temperature reactors cooled by helium gas or molten salt; liquid metal reactors cooled by sodium, lead, or lead-bismuth eutectic; and reactor technologies that feature liquid fuel dissolved as fissile and fertile materials in molten salt coolant.

Advanced reactor technologies offer key performance features such as:

- **Improved Economics** Once the demonstration is completed through the first-of-a-kind unit and a supply chain is established, it is expected that construction and operation costs will be lower than current reactors.
- **Higher Outlet Temperatures** Higher temperatures produce electricity more efficiently and can better replace fossil fuel generated heat for some industrial applications such as chemical production, hydrogen production, and water desalination.
- **Enhanced Inherent Safety Systems** Mechanisms are designed to shut down the reactor and remove decay heat effectively even in the event of a full station blackout, such as occurred at Fukushima. These mechanisms help the facility withstand many extreme accident scenarios.
- **Advanced Fuels in Various Forms** Liquid, particle, metallic, or ceramic and new cladding materials will operate at higher temperatures, extract more energy from the fuel, tolerate a wider range of operating conditions, reduce waste generation, and improve proliferation mitigation.
- **Advanced Power Conversion Systems** Gas turbines or supercritical fluids will reduce water usage and increase efficiency.

Many of these concepts are also applicable to SMR designs. For certain markets, higher temperature applications for process heat and improved fuel characteristics that facilitate storage and disposal may offer a preferred option. U.S. advanced nuclear technologies need to be available for commercial deployment by 2030 if the U.S. is to obtain a substantial share of the global market for these technologies.

By 2050, these new technologies could coexist with large LWRs and light water cooled SMRs. Inaction by the U.S. until these technologies are commercially available would mean relinquishing the technological and industrial leadership to competing nations.

The rapid and diligent progress with light water SMR deployment could be just a necessary first step towards a future where U.S. technological and industrial leadership is maintained. The deployment of light water SMRs would enable the establishment of a strong supply chain that will be beneficial for subsequent technologies, and it will provide a robust intellectual and physical infrastructure supporting the nuclear industry.

Summary

- This is not a call for a new research program.
- Current efforts to maintain the nuclear fleet are important but are insufficient alone to sustain U.S. nuclear energy capability.
- The next step could be to deploy SMRs.
- The installation of SMR capability would provide a bridge to a future with advanced capabilities.
- SMRs will not be deployed without government encouragement. Their cost is higher than natural gas options, unless the cost of carbon is factored in by using a carbon tax or similar subsidy. In addition, SMRs are valued as an essential component for nonproliferation goals. Regulatory barriers would need to be addressed.
- One concrete example of the readiness of an SMR design has been developed by NuScale Power. There is already activity toward deployment of these SMRs. In the long run, retiring nuclear and coal capacity along with increasing electricity demand present a market opportunity for new nuclear deployment.

Chapter 3—Fuel Leasing/Interim Storage to Disposition

A significant percentage of this century's growth in nuclear power will take place in developing countries. In this growing market, traditional nuclear-supplier states are being supplanted by a new suite of vendors. None have a deep-rooted history in upholding international nonproliferation norms and safety standards. As nuclear technology spreads to more countries, how can the diversion of nuclear material to weapons uses be prevented and how can the safe storage and disposal of nuclear waste be assured?[48]

Since the dawn of the Atomic Age, observers have worried that the spread of nuclear power might lead to possible proliferation. Previous proposals for the international control of nuclear material date back to the Baruch Plan of 1946, which eventually led to negotiation and adoption of the Nuclear Non-Proliferation Treaty (NPT) in 1970. Nonproliferation efforts continue with recent considerations of nuclear fuel banks.[49] Under the terms of Article IV of the NPT, signatories have the "inalienable" right to use nuclear materials and facilities for peaceful purposes; they agree, under Article II, not to pursue nuclear weapons.[50] Upon gaining access to adequate technological capability, particularly technologies for enrichment and reprocessing that result in the ability to produce weapons-usable fissile material, countries have cheated or—in the case of North Korea—withdrawn from the NPT in their pursuit of a nuclear weapons program. Some countries have argued that they need to develop their own enrichment or reprocessing capability. The fundamental principle behind an international fuel bank is to preclude such arguments by providing a guaranteed fuel supply to any country reliant on nuclear power, thereby negating any requirement for enrichment or reprocessing technology.

Russia has operated a low-enriched uranium (LEU) bank since 2010, and the IAEA has just completed such a facility in Oskemen, Kazakhstan that can be a physical reserve for 90

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[48] Nikitin, Mary Beth, Anthony Andrews and Mark Holt, "Managing the Nuclear Fuel Cycle: Policy Implications of Expanding Global Access to Nuclear Power," Congressional Research Service (19 October 2012) available at: https://fas.org/sgp/crs/nuke/RL34234.pdf.

[49] For a cursory overview of this history, see Randy Rydell, "Going for Baruch: The Nuclear Plan that Refused to go Away," Arms Control Today available at: https://www.armscontrol.org/act/2006_06/LookingbackBaruch.

[50] https://www.iaea.org/newscenter/pressreleases/iaea-leu-bank-reaches-milestone-with-storage-facility-inauguration-in-kazakhstan.

megatons (MT) of low-enriched uranium.[51] The establishment of one or more additional international fuel banks has been proposed.

Unless a country has intentions beyond addressing its energy demands, the financial incentives not to pursue full fuel-cycle capabilities are quite persuasive. However, the international fuel bank idea has yet to take hold, and it does not address the problems surrounding storage and disposal of nuclear waste.

Geologic Repository

Although a number of foreign countries have planned for the storage and disposal of their indigenous waste, no progress has been made in providing international or regional facilities for the disposal of high-level nuclear waste and spent fuel. Geologic disposal of high-level nuclear waste is widely recognized as the preferred means of storage. Four countries—the U.S., Sweden, France, and Finland—have sited geologic repositories for this purpose. It is not credible to believe that every country that has nuclear power now or in the future will have the indigenous capability to geologically dispose of their high-level waste and spent fuel. This problem must be addressed and resolved if nuclear energy is to play a major role in carbon-free energy production in the future.

Fuel Leasing

Concerns about proliferation and the safe storage and disposal of nuclear waste can be overcome in large part if the U.S. proceeds with its interim storage and disposal capability and offers to lease fuel to other countries. The U.S. would provide enriched uranium fabricated into fuel and receive used leased fuel back for disposition. Fuel leasing helps prevent access to weapons-usable nuclear material.[52] Any act by a host country to keep spent fuel would be a clear and unambiguous violation regardless of their rights under the NPT. The offer to take care of fuel-cycle issues should be valuable to client countries while respecting the rights of NPT signatories. A leasing program also would facilitate U.S. nuclear reactor exports.

The concept of fuel leasing or fuel return is not new. The U.S. has practiced this on a small scale for fuels associated with research reactors provided under the Atoms for Peace initiative, with significant nonproliferation and security benefits, since some of these fuels were more highly enriched in fissile uranium than commercial reactor fuel. Russia has instituted a return policy for fuels used by Russian reactors in foreign countries or under other special circumstances, such as

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[51] See Treaty on the Non-Proliferation of Nuclear Weapons available at: https://www.iaea.org/sites/default/files/ publications/documents/infcircs/1970/infcirc140.pdf.

[52] See, for example, Braun, Chaim and Michael May, "An International Regime of Fresh Fuel Supply and Spent Fuel Disposal," Nonproliferation Review, Vol. 13, No 1 (March 2006). Also, Paine, Christopher E. and Thomas B. Cochran, "Nuclear Islands: International Leasing of Nuclear Fuel Cycle Sites to Provide Enduring Assurance of Peaceful Use," Nonproliferation Review, Vol. 17, No. 3 (November 2010).

the Bushehr nuclear power plant in Iran. The ability of Russia to provide fuel services and their return fuel policy is viewed as a competitive advantage in the international nuclear supplier's market. All of the major nuclear power countries shown in Figure 6 have the intention of developing nuclear repositories in the future.[53] These nations typically have ten or more power reactors and in some cases plan to include reprocessing as part of their fuel cycle.

Top Ten Nuclear Generating Countries—2016, Billion kWh

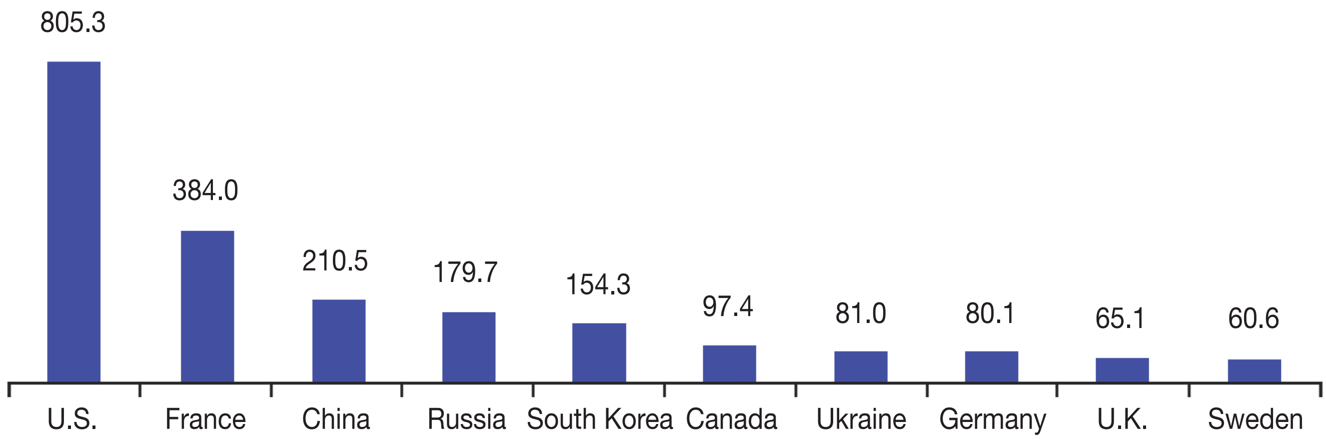

Figure 6. Top Ten Nuclear Generating Countries—2016, Billion kWh.
Source: International Atomic Energy Agency, updated 4/17.

Approximately twenty nuclear power nations have only a few reactors; development of a stand-alone repository for disposal for them is impractical. Instead, they seek to create and participate in multinational fuel-cycle facilities, and they have been actively participating in international efforts to promote these concepts.[54]

U.S. reactor sales to countries that already have significant nuclear programs are not likely to require fuel leasing. For emerging members of the nuclear power community, however, fuel leasing services would be highly desirable and an incentive to purchase U.S. reactor technology.

Other nuclear reactor supplier nations should be encouraged to offer similar leasing programs. In any case, the amount of fuel returned to the U.S. is likely be small. For example, Mexico has two U.S. supplied reactors and may build additional units within the next ten years. By 2048 the total amount of spent fuel stored in Mexico would be less than 1 percent[55] of the projected U.S.

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[53] Figure 6 from NEI on Top 10 Generating Counties. https://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics/Top-10-Nuclear-Generating-Countries.

[54] Reference IFNEC document. International Framework for Nuclear Energy Cooperation Reliable Nuclear Fuel Services Working Group; Practical Considerations to Begin Resolving the Final Spent Fuel Disposal Pathway for Countries with Small Nuclear Programs; October 2016.

[55] https://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/NFC/documents/spent-fuel/TM-47934-2014/Agenda-14-Mexico-Molina.pdf.

inventory of 217,000 MT spent nuclear fuel plus high-level waste.[56] Similarly, Taiwan would have spent fuel amounting to about 2 percent[57] of U.S. inventory. The total leasing program will probably require the reservation of no more than 15 to 20 percent of U.S. storage and disposal capacity for international leasing commitments.

Although there are many ways to provide fuel leasing services, one approach might consist of the following steps:

- A U.S. reactor vendor would select a U.S. based fuel fabricator to provide a lifetime fuel supply for a reactor to be sold to a foreign country.
- The U.S. government would enter into a contractual arrangement with the vendor to commit the U.S. government to accept the used fuel at a U.S. site for interim storage and then ultimate disposition.
- The full cost-plus-profit for the fuel, including enrichment, fabrication, energy production, and transport, would be established by the vendor.
- The full cost for receipt, storage, and disposition would be established by the U.S. government.
- All fuel lease costs would be charged to the lessee.
- Title to the fuel would remain with either the U.S. vendor or U.S. government with title transfer occurring at, or no later than, delivery to the U.S. government storage site. The title could transfer to the U.S. government at an earlier time if doing so would have greater nonproliferation benefits.

Other major nuclear power countries with significant inventories of material for permanent disposition (e.g. France, United Kingdom, China) may find it beneficial to follow the U.S. lead. If the U.S. and other countries were to provide fuel leasing services, they would essentially be providing the same services as a fuel bank with international storage and disposal capability.

The benefits of U.S. fuel leasing include:

- The fuel remains in non-weapons usable form and its ownership is maintained by a U.S. company or the government.
- Any attempt by the lessee to keep or divert fuel is a clear, unambiguous violation.
- The U.S. government decides on the disposition of used nuclear fuel.
- All costs would be borne by lessee.
- The ability of U.S. vendors to offer fuel leasing services provides a very strong marketing advantage.

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[56] U.S. Nuclear Waste Technical Review Board, Spent Nuclear Fuel and High-Level Waste in the United States, March 2016.

[57] http://www.aec.gov.tw/english/radwaste/file/national_report_2016.pdf.

- The lessee does not need to dispose of the used fuel or await the availability of international or regional disposition services.

One statutory change needed for a fuel leasing program to proceed is to expand the U.S. government's legal authority to accept fuel from a foreign country. The U.S. currently has the authority to accept foreign spent fuel for storage and disposal under the Nuclear Non-Proliferation Act of 1978 (NNPA) (see box below); however, each return requires a presidential determination and review by Congress. To enable fuel leasing as proposed, legislation would need to be enacted to allow the U.S. government to enter into a contractual agreement with U.S. reactor vendors to offer such services as part of sales to foreign customers. The potential of achieving this change may be increased by the connection between securing nonproliferation objectives and retention of ownership of the fuel by U.S. companies or the U.S. government. In addition, as stated before, the amount of foreign fuel would be very small compared with the amount of U.S. origin spent nuclear fuel (SNF) needing disposal.

A fuel leasing program also requires the capability to accept waste for interim storage and the capability for its permanent geologic disposal. The ability to accept SNF from the fuel leasing program will require the U.S. to provide for storage of fuel in dry storage casks at a suitable site in the U.S. The ultimate disposal of this SNF is a more difficult problem, as the U.S. government has not yet licensed a repository. (See the text box, Siting of Geologic Repositories, page 30.)

The broader contours of the issues facing nuclear waste disposal in the U.S. go beyond the needs of a possible leasing program and would have to be addressed. The U.S. government has both statutory and contractual obligations to receive SNF from U.S. utilities. Statutory limits on the amount of SNF or waste that can be accepted at the first U.S. repository have already been exceeded by waste currently stored at reactor sites. Either the SNF storage limit must be increased, or another repository must be sited and licensed.[58] It seems obvious that a prerequisite for foreign fuel leasing would be for the U.S. government to begin making good on its obligation to take SNF from U.S. utilities.

In 2012, the Blue Ribbon Commission on America's Nuclear Future made a number of recommendations for proceeding with DOE's program for the management of nuclear waste. Its recommendations included the establishment of one or more interim storage facilities for SNF, prior to the licensing of a permanent geologic repository. It also called for the formulation of a consent-based process for the siting of both storage facilities and a geologic repository for permanent disposal of high-level waste and SNF.[59] The Blue Ribbon Commission further described "spent-fuel 'take-away' arrangements" and endorsed a mechanism very similar to the fuel leasing

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[58] A report looking at market-based mechanisms for disposition also argued for U.S. acceptance of foreign spent fuel. See Ferguson, Charles D., Clifford Singer, Jack Spencer and Sharon Squassoni, "U.S. Spent Fuel: A Market Based Solution," Center for Strategic and International Studies (May 2011), pp. 5-7.

[59] Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy (January 2012), https://energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf.

program described in this chapter.[60] Some of the other recommendations of the commission, such as making funds collected for the nuclear waste program more readily available for that purpose, are useful to ensure that any funds for storage and disposal collected through a fuel leasing program are similarly available.

It is not clear whether and when Congress or the administration will act on the Blue Ribbon Commission recommendations. The administration apparently plans to restart the licensing process for Yucca Mountain.

Regardless of the status of Yucca Mountain, the government will need one or more facilities to accept spent fuel for interim storage will be needed in the near-term, and one or more geologic facilities will be needed in the long-term, to meet U.S. requirements. The concept advanced by the Blue Ribbon Commission of a more adaptive, staged, and consensual process for siting waste storage and disposal facilities has substantial merit. Because the commission decided not to specify in detail how the process would work, there needs to be a backstop to ensure that the U.S. government meets its responsibilities in this area if a more consensual process breaks down.

The path to providing fuel leasing services for foreign reactor sales is straightforward but rocky. The hurdles need to be cleared expeditiously for such services to be relevant and beneficial to the global deployment of nuclear reactors over the next twenty-five years. The preparations to offer fuel leasing services should not be dependent upon the immediate availability of a geologic repository: siting, licensing, and construction would take too long. But the processes to license, construct, and operate one or more geologic repositories need to be restarted. If implemented in a timely manner, a fuel leasing program would be most useful to U.S. and global security interests.

Although siting interim consolidated storage facilities might face many of the same political problems of siting a geologic repository, dry-cask storage facilities already exist at many locations and establishing consolidated facilities would not require the exhaustive characterization and licensing process of a geologic repository. The same process that is chosen for the selection of a long-term site, including local consent and approval, could also be applied to selecting sites for additional interim storage facilities. For this reason, there should be legislation to make the needed statutory changes to enable a process to select, license, construct, and operate one or more interim consolidated storage facilities, for both domestic and foreign SNF, and to authorize foreign fuel leasing.

Existing repository capacity limitations should be increased. Restarting would require congressional appropriations and increasing the capacity limitations would require legislation.

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[60] Ibid., pp. xv, 114-115.

Siting of Geologic Repositories

Efforts in the U.S. to site and construct a geologic repository for high-level nuclear waste and spent fuel from commercial reactors have not yet been successful. The U.S. Atomic Energy Commission identified salt formations near Lyons, Kansas in the early 1970s but ended consideration of this site when bore holes through the salt deposits were discovered. No further progress was made until the passage of the Nuclear Waste Policy Act (NWPA) of 1982. That act prescribed a process to site, approve, license, construct, and operate two geologic facilities, and it authorized the Office of Civilian Radioactive Waste Management within the DOE to enter into contracts with utilities and collect 1 mill per kWh ($0.001 per kWh) for the disposal of nuclear waste. Sites in Nevada, Washington, and Texas were selected for detailed characterization in 1986. However, in 1987 Congress amended the act and identified Yucca Mountain as the sole site. In 2002 Yucca Mountain was formally found suitable and in 2008 a license application was submitted and accepted by the NRC. With the change of administrations in 2009, further work on Yucca Mountain was suspended and efforts were made to withdraw the license application. The D.C. Circuit Court of Appeals ruled in 2013 that the administration could not withdraw the license application, and the current administration has expressed intent to renew the licensing process.[61]

The siting of a geologic repository is a political issue. Prior to the selection of Yucca Mountain, the NWPA was amended in 1987. Under the original act, three sites would be characterized in sufficient detail to enable a technically sound, science-based selection of a preferred site. It was anticipated that all sites would have benefits and challenges and a selection process based upon three equally characterized sites would be more defensible if and, most likely, when the selected host state vetoed the selection. Unfortunately, neither Washington nor Texas was fully characterized when the act was amended in 1987.

The Blue Ribbon Commission on America's Nuclear Future has recommended that a new consent-based process be used for the siting of geologic repositories. In defining consent, the commission "takes the view that this question ultimately has to be answered by a potential host jurisdiction, using whatever means and timing it sees fit."[62] Although certainly desirable that there be a means of resolving conflicts when all involved parties are not in agreement, it is still necessary to have confidence that a storage or disposal facility will be sited. Experience at Yucca Mountain and initially DOE's Waste Isolation Power Plant (WIPP) has shown that local governments are supportive of site selection, while state governments often are not. In general, support for nuclear facilities is inversely proportional to distance from the host community where the benefits of and knowledge about the facilities and technology are

[61] http://www.reuters.com/article/us-usa-trump-budget-nuclear-idUSKBN16N0D5.

[62] Ibid., pp. xv, 114-115., p. ix.

greater. Therefore, although the Blue Ribbon Commission agreed on the benefits and desirability of achieving full consent, a process to ensure that the U.S. government can fulfill its responsibilities for safe, permanent disposal of nuclear waste, despite the objections of one or more parties will most likely be necessary. The original NWPA of 1982 had such a process that could serve as a model.

In addition to the consent-based process recommended by the commission, there is merit to proceeding with Yucca Mountain's license application. This will help determine if it is licensable with an option not to proceed with construction until either consent is achieved or other sites are characterized and considered. A decision on the license application, even if favorable, does not guarantee a repository will be built at the site given the past history of the selection process involving Yucca Mountain. Another option would be to explore the willingness of individual states to host a repository. An example would be to approach New Mexico and the appropriate local governments to broaden the current mission of the WIPP site to include facilities for the storage or disposal of commercial spent nuclear fuel. Another option would be to explore interest in storage-only or combined storage and disposal facilities at other locations where suitable transportation and infrastructure could be developed.

Nuclear Non-Proliferation Act of 1978 (NNPA) and the McClure Amendment

The U.S. is perhaps the only major nuclear power that allows for the receipt and disposal of foreign-origin spent fuel. Embedded within the NNPA of 1978 is a provision that requires a subsequent arrangement that "involves a direct or indirect commitment of the United States for the storage or other disposition, interim or permanent, of any foreign spent nuclear fuel in the United States"[63] (42 U.S.C. 2160(f), otherwise known as the McClure Amendment of the NNPA). The requirements and conditions for this subsequent arrangement include a presidential determination of need, specifics as to how and where the fuel will be managed and disposed, and submission to various congressional committees and, ultimately, for a sixty day congressional review. Although not insurmountable, the barriers imposed prevent any meaningful effort to implement provisions of the NNPA to encourage fuel returns as a means of achieving U.S. nonproliferation objectives.

[63] U.S. Code › Title 42 › Chapter 23 › Division A › Subchapter X › § 2160, available at https://www.law.cornell.edu/us-code/text/42/2160. The McClure Amendment forms the basis for §2160 (f) (1) (A).

Summary Chapter 3

- The offer of a fuel leasing program as part of a sale of a reactor to a foreign client would greatly relieve concerns about proliferation and safe storage and disposal of nuclear waste. Most clients would be expected to favor accepting a lease and delegating the fuel disposal back to the U.S. Regardless of the rights of a client assured under the NPT, any client keeping the fuel would be in clear violation and its actions could be immediately detected.
- Efforts to install a repository for high-level nuclear waste and spent fuel in the U.S. have stalled after significant research and funding. Yucca Mountain is the only site that has been characterized, and work on its license application has been suspended, although the current administration has indicated it is planning to restart the process.
- A leasing program would require a combination of temporary dry-land storage and long-term underground storage at a repository. The amount of fuel from a fuel leasing program is expected to be small. Fortunately, dry-cask storage could provide a temporary solution long enough to establish a safe and acceptable geologic repository.

Additional References

1. Pentz, D.L. and R.H. Stoll, "Commercial Nuclear Fuel Leasing–The Relationships to Nonproliferation and Repository Site Performance," Waste Management Conference (February 25-March 1, 2007).
2. Reis, V.H., M.P. Crozat, J-S Choi and R. Hill, "Nuclear Fuel Leasing, Recycling and Proliferation: Modeling a Global View" (March 2004).

Chapter 4—International Safety and Operational Excellence

The U.S. must regain and sustain public and political confidence in the nuclear power enterprise by ensuring the safe and reliable operation of its existing fleet of reactors, and by promoting new SMR designs that are recognized to be ultra-safe by relying on inherent and passive safety design and operational features.

The Safe and Reliable Operation of the Current Fleet of Nuclear Power Reactors

To sustain a viable nuclear power industry in the U.S., nuclear plant owners must continue to maintain a high level of reliability and safety through operational excellence at their units. Over the past several decades reliability and safety trends indicate continuous and positive improvement.[64] All of the reactors currently operating meet or exceed the safety goals established by the NRC.

Capacity factors for U.S. nuclear reactors are shown in Figure 7.[65] A high capacity factor means a high ratio of produced energy to rated capacity. The EIA reported[66] that the average capacity factor of U.S. nuclear reactors for the five year period of 2008–2012 was 90 percent. This is an indicator of the excellent reliability of the nuclear power performance in the U.S. and consequently the safety of the plants.

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[64] See https://www.nei.org/Issues-Policy/Safety-and-Security.

[65] Figure 7 is taken from Nuclear Energy Institute website: see https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Capacity-Factors.

[66] in September 2015 [https://www.eia.gov/todayinenergy/detail.php?id=22832].

Sustained Reliability and Productivity—U.S. Nuclear Capacity Factor, Percent

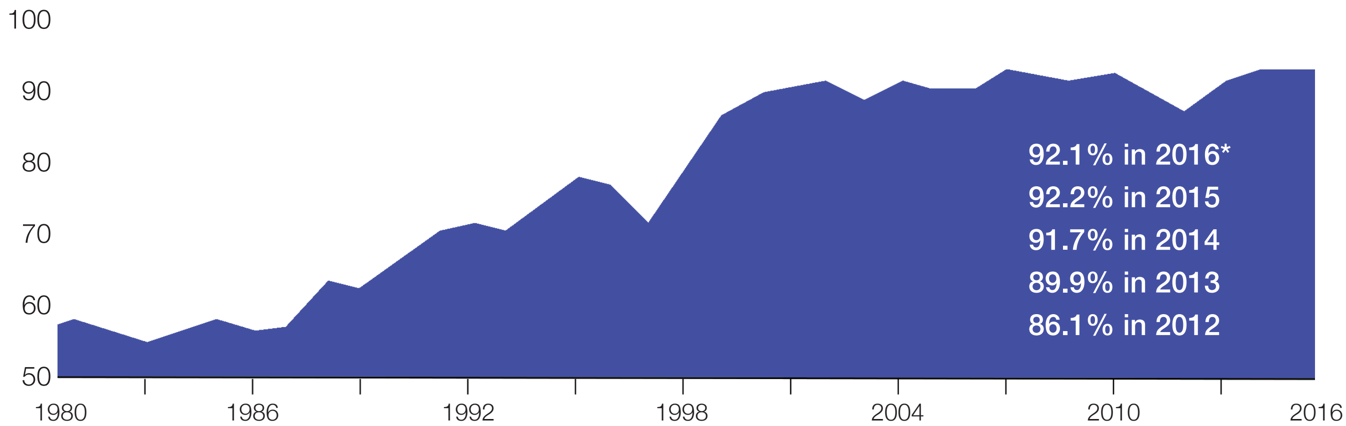

Figure 7: Capacity Factors for U.S. Nuclear Power, 1980–2016.
Source: Energy Information Administration, updated 3/17.
**EIA states the capacity factor for nuclear is 92.5% but does not include the capacity for Fort Calhoun, Nebraska. NEI included Fort Calhoun in the nuclear capacity factor value.*

Despite the nuclear industry's strong safety record in the past few decades, it should reduce even further the probability of future potential accidents, especially those that could have public impact such as radiation releases. To accomplish this, the U.S. nuclear industry must make sure that effective mitigation features and accident management procedures are in place. The protection should be sufficient to accommodate events of considerable severity, such as the 2011 events at the Fukushima Daiichi plant. (See the text box on Fukushima: U.S. Safety Standards and Steps for Prevention, page 37.) To take advantage of the lessons learned from that accident, the industry and the NRC undertook studies and actions to ensure the safety of U.S. nuclear power plants.[67] These include upgrading procedures and equipment to respond to extreme external events, such as floods and earthquakes, and to ensure that emergency preparedness is adequate for such unlikely events.

The U.S. industry follows the standards of the U.S.-based Institute of Nuclear Power Operations (INPO). INPO promotes the highest levels of safety and reliability in the operation of commercial nuclear power plants. By working with international organizations such as the World Association of Nuclear Operations (WANO), the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, and the IAEA, the U.S. can influence safety trends in other countries that plan for or operate nuclear power plants. For example, the continued sharing of best practices among organizations such as INPO and WANO enhances safety everywhere. The loss of a U.S. nuclear power program and INPO would diminish the capability of the international groups.

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[67] A summary of the various actions and improvement to U.S. plants since 2011 is given at https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/japan-events.html. The industry developed diverse and flexible coping strategies (termed FLEX) to respond to extreme events that would challenge U.S. plants (see NEI 12-06, August 2012, see https://www.nrc.gov/docs/ML1222/ML12221A205.pdf.

For the continuing viability of nuclear energy in the U.S., the Price-Anderson Nuclear Industries Indemnity Act, which governs liability-related issues for all nonmilitary nuclear facilities constructed domestically before 2026, will need to again be renewed.

The U.S. nuclear industry and the NRC have done much work in the area of applying probabilistic risk assessments to reactor safety issues over the past four decades. The continuation of these efforts will help to improve safety and operations. In the context of probabilistic risk, the Linear No-Threshold (LNT) model of the effects of low-dose radiation on human health needs to be revisited.[68] Advances in genomic medicine will enable a more rigorous assessment of these effects.

New Reactor Design: Safety Advantages of SMRs

Many new SMR designs have emerged worldwide over the past decade. (See Figure 8.) This table is a snapshot of SMR activity; the picture changes frequently as research results add or eliminate approaches. The key point is that this is an active process in many countries, even those with current nuclear energy infrastructure.

IAEA Member States with SMRs

ARGENTINA
CAREM

CANADA
LEADIR-PS
IMSR

CHINA	
HTR-PM	CAP150/200
ACP100	ACPR50S

DENMARK
MSTW

FRANCE
FLEXBLUE

INDIA
AHWR-300

JAPAN	
4S	IMR
GTHTR300	FUJI
DMS	

REPUBLIC OF KOREA
SMART

RUSSIAN FEDERATION			
KLT-40S	SHELF	ELENA	MHR-T
RITM-200	UNITHERM	RUTA-70	SVBR-100
ABV-6E	KARAT-100	GT-MHR	BREST-OD-300
VBER-300	KARAT-45	MHR-100	

SOUTH AFRICA	
PBMR-400	HTMR-100 SMR

UNITED KINGDOM
Stable Salt Reactor

UNITED STATES OF AMERICA		
NuScale	SC-HTGR	LFTR
mPower	Xe-100	SmAHTR
W-SMR	EM^2	Mk1 PB-FHR
SMR-160	G4M	

Figure 8. IAEA Member States with Small Modular Reactors.
Source: IAEA report https://aris.iaea.org/Publications/SMR-Book_2016.pdf.

[68] House Subcommittee on Energy Hearing-The Future of Low Dose Radiation Research. October 2017, https://science.house.gov/legislation/hearings/subcommittee-energy-hearing-future-low-dose-radaition-research.

Although SMR designs can potentially offer safety advantages, as described in Chapter 2, not all of the proposed designs possess the highest-level safety characteristics outlined there. All designs would be subject to scrutiny by the regulatory authorities to which they are being proposed.

Desirable characteristics of SMRs that would enhance their safety are:

- A lower radiological inventory in the reactor core relative to the current fleet of large power reactors.
- Safety systems that are relatively simple and can function to reduce the potential for severe reactor accidents and their consequences.
- Inherent and passive safety features (e.g. natural convection cooling without pumps).
- Decay-heat removal systems that are relatively less complex as well as highly reliable.
- Longer time periods before safety systems at the plant are needed to mitigate an accident, thus allowing time for appropriate operator response (if needed).
- Defense-in-depth features of the overall plant to assure there are multiple barriers to radioactive releases in the event of an accident.

There are also potential benefits from SMRs because of their relatively small size. Emergency planning in the event of an accident would be simplified, as would physical protection in the event of hostile acts. Potential benefits can result from appropriate operational staffing of multiple small modular units.

Probabilistic risk assessments have been performed for SMR concepts over the past few years. Risk studies of new concepts cannot be performed with as much detail on plant performance and operational data as would be done for an existing operating reactor. However, trends from the studies of SMR concepts suggest that the potential for radiological consequences are much lower than for the current generation of reactors. The risks posed by the current fleet of nuclear power plants in the U.S. are already acceptably low with regard to the safety goals formulated by the NRC.[69]

Although not all SMRs proposed by various countries offer the same degree of safety in all aspects, if the U.S. selects a design, or designs, with strong and robust safety characteristics, it can potentially influence other countries—particularly newcomer countries to nuclear power—to choose designs that also possess a very high degree of safety. It will be important to have the U.S., with its extensive knowledge and practical base in reactor safety, serve as a guide for emerging nuclear power countries in the coming decades.

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[69] See Nuclear Regulatory Commission, “Safety Goals for the Operations of Nuclear Power Plants; Policy Statement; Republication,” 51 Fed. Reg. 30028 (August 21, 1986), available at https://www.nrc.gov/reading-rm/doc-collections/commission/policy/51fr30028.pdf.

Fukushima: U.S. Safety Standards and Steps for Prevention

The U.S. has been the global leader in international nuclear safety since the inception of nuclear power in the early 1950s, and continues to lead in promoting nuclear safety culture and the understanding potential hazards and consequences. For more than sixty years the U.S. has based its technology and regulations on a principle of defense-in-depth. That principle continues today as the government and industry work on concepts to improve the existing fleet and develop designs for advanced reactors.

For example, after the events of September 11, 2001, the U.S. undertook a rigorous analysis of “severe accident scenarios.” These accident scenarios would lead to a condition called “station blackout,” where no alternating current is available for the reactor, which could result in failure of the systems needed to cool the reactors. Working together, regulators and industry developed mitigating measures to address a station blackout and to continuously train for implementing these countermeasures.

Some nations were quick to follow the U.S. lead, others were not. One of the nations slow to adopt U.S. standards was Japan. On March 11, 2011, a massive earthquake and resulting tsunami destroyed critical infrastructure at the Fukushima Daiichi site resulting in a station blackout. The core melt-down at three of the reactors can be attributed to the inability of the operators to recover from the station blackout. It is impossible to say if the accident could have been prevented but it is understood that lack of preparation contributed to the failure.

Unless the U.S. once again becomes a relevant technology leader, its traditional role in leading and influencing high standards in new nuclear power technologies and “best practices” in safety will diminish as other nations become the providers of choice.

Summary Chapter 4

- The U.S. safety record has been high and is still improving. The U.S. follows the highest global standards from the INPO, which coordinates with and influences WANO and others.
- The industry should continue to take advantage of the lessons learned from accidents such as Fukushima and upgrade procedures and equipment to respond adequately to extreme events.
- The U.S. should leverage its knowledge and experience in nuclear reactor safety to offer and provide help to the global nuclear industry.
- Probabilistic risk assessments of the safety of new reactor concepts should be strongly encouraged. Similarly, the LNT model of low radiation effects on human health should be revisited.

Conclusions

Background

- Nuclear energy is expected to grow by several multiples through 2100 in response to increasing global electricity demand and the need to limit GHG emissions. The future calls for four approaches to satisfy energy demand—increased efficiency, renewables, nuclear, and carbon capture and sequestration. The failure to successfully pursue any of these will put a burden on the others.
- Nuclear energy will be needed in partnership with three other approaches—increased efficiency, renewables, and carbon capture and sequestration—to meet future energy demands.
- If present trends continue, the U.S. will soon be phased out of the nuclear energy business.

Potential Paths Forward

- Revitalize the domestic civil nuclear energy program. Otherwise, future nuclear power plants will be built and managed by other countries that do not necessarily share the U.S. expertise in and concern for safety and nonproliferation. Without a domestic industry, the U.S. will lose the expertise in nuclear engineering and related research that would, for example, help it to counteract groups intending to use nuclear material for harmful purposes.
- Encourage the deployment of SMRs in the next twenty years as a bridge toward an era with next generation reactors. SMRs are small enough to be manufactured off-site at a factory. Such factories would offer many advantages in terms of cost, safety, proliferation, and flexibility. Most importantly, SMRs are ready to license and build now. The presence of a robust nuclear power system will allow utility executives to manage risks associated with natural gas price increases and with the inevitable rise of the cost of emitting carbon to the atmosphere. If a bridge to a U.S. nuclear future can be started, further advanced nuclear technologies will offer more efficient use of uranium fuel and facilitated waste disposal along with continued improvements in cost, safety, and nonproliferation.
- Develop a fuel leasing program for reactor sales to other nations. In the wrong hands, a nuclear power plant reduces the time needed for the development of nuclear weapons. Because the point of sale is where limits are best asserted, a fuel leasing agreement with the client greatly reduces the risks. To proceed with fuel leasing programs, the U.S. must develop a capability to dispose of commercial nuclear waste. Waste disposal is possible in the short term with dry-land storage and in the long term with a geologic repository.

- Continue to improve the safety of existing and future facilities. Heightened vigilence is important not only for avoiding accidents but also for building the trust of the public in the nuclear option. A strong U.S. nuclear program achieves the highest safety requirements and procedures and improves on them. The U.S. also helps and influences other countries to improve the safety of their operations.

Table of Figures

Novim Nuclear Energy Study Participants

Dr. Gerald M. Stokes (Study Chair)—Dr. Stokes is a research professor at Stony Brook University. He was a long-time employee of Battelle, serving as an associate laboratory director at PNNL and BNL, as well as president and CEO of Battelle-Japan. He was the first chief scientist of DOE's ARM program and founding director of the Joint Global Change Research Institute.

Dr. Aristides A. N. Patrinos (Study Vice Chair)—Ari Patrinos is chief scientist and director of research at Novim. Following twelve years as a researcher at DOE national labs, he was director for biological and environmental research at DOE for twenty years. He was president of Synthetic Genomics Inc. for five years and then a New York University professor of Mechanical and Biochemical Engineering (currently on leave). During 2016 he served as senior adviser to DOE Secretary Moniz.

Dr. John C. Houghton (Rapporteur)—Dr. Houghton managed research programs in the DOE's Office of Biological and Environmental Research for twenty-five years. He was an office director in ARCO Oil and Gas Company's Corporate Research Laboratory and served in several positions at the U.S. Geological Survey. He was a senior policy analyst in the Office of Science and Technology Policy in the Carter White House and a research scientist in the Massachusetts Institute of Technology Energy Laboratory.

Dr. Robert Bari—Senior physicist at Brookhaven National Laboratory, Dr. Bari is currently international cochairman of the working group that has developed a comprehensive methodology for evaluation of proliferation resistance and physical protection of all new nuclear energy concepts being proposed within the multinational Generation IV International Forum. He was a member of a committee of the U. S. National Academy of Sciences on Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of the U.S. Nuclear Plants. In 2004, he received the Brookhaven National Laboratory Award for Outstanding Achievement in Science and Technology. Dr. Bari is an elected fellow of the American Nuclear Society and of the American Physical Society.

Mr. Paul Dickman—Mr. Dickman is a senior policy fellow with Argonne National Laboratory, focusing on nuclear energy, safety, and national security policy. For over thirty-five years he has been involved in the forefront of nuclear energy and national security programs in the U.S. and internationally. He has held senior managerial positions at the NRC and DOE's National Nuclear Security Administration. Mr. Dickman holds leadership positions in the American Nuclear Society and the World Council on Isotopes and advises organizations on risk communication. He also serves as a special international advisor to the Japanese government on the decommissioning and remediation of the Fukushima accident site.

Dr Alan S. Icenhour—Dr. Icenhour is the associate laboratory director for the Nuclear Science and

Engineering Directorate at the Oak Ridge National Laboratory (ORNL). His more than thirty years of nuclear experience has included reactor operations and research and development on topics such as enrichment, radiochemical processing, radioisotope production and applications, nuclear fuels, radiation effects on materials, radioactive waste management, and nuclear security. Prior to joining ORNL, he served as a submarine officer in the U.S. Navy.

Mr. Michael Lawrence—Mr. Lawrence was managing director of the United Kingdom's National Nuclear Laboratory from 2009 until the end of 2010. He was manager of DOE's Richland Operations Office from 1984 until 1990, and counselor of nuclear policy at the U.S. Mission to United Nations Organizations in Vienna, Austria from 1991 to 1995. From 2000 to 2010, he worked for Battelle as associate laboratory director for energy and information technology and deputy director for campus development at the Pacific Northwest National Laboratory in Richland, Washington, before being selected in 2009 as managing director of the UK National Nuclear Laboratory.

Dr. Kemal Pasamehmetoglu—Dr. Pasamehmetoglu has been with Idaho National Laboratory (INL) since 2004, most recently serving as the Associate Laboratory Director for the Nuclear Science and Technology Directorate, where he was instrumental in the launch of the Gateway for Accelerated Innovation in Nuclear Initiative. Prior to his time at INL, he held senior technical leadership positions at Los Alamos National Laboratory. Dr. Pasamehmetoglu also served as the National Technical Director for Advanced Fuels Research and Development in the Advanced Fuel Cycle Initiative. He holds a doctorate in mechanical engineering from the University of Central Florida and has thirty years of research and engineering experience within the national laboratory system.

Dr. Victor Reis—Retired from the DOE after ten years as senior advisor, Dr. Reis's government service included assistant secretary of energy for defense programs, director of defense research and engineering and director of the Defense Advanced Research Projects Agency (DARPA), and assistant director for national security and space at the White House Office of Science and Technology Policy. He also was senior vice president at Science Applications International Corporation, and senior staff at Lincoln Laboratory; and served on advisory groups and boards or the director of the Central Intelligence Agency, U.S. Strategic Command, DOE, U.S. Navy, Department of Defense, NASA, and Argonne, Sandia, Los Alamos, and Idaho national laboratories.

Dr. Robert M. Simon—Dr. Simon is an independent energy consultant, was the Democratic staff director of the U.S. Senate Committee on Energy and Natural Resources from 1999-2012. From 2013 to 2016, he served in the White House Office of Science and Technology Policy, where he was principal advisor to the director for energy, transportation, and resources. He is currently a member of the advisory board for Protect Our Power, a nonprofit concerned with the security of the electric grid.

Dr. Elizabeth (Libby) Turpen—Currently president of Octant Associates, LLC, Dr. Turpen is also an adjunct at the Institute for Defense Analyses (IDA). She offers consulting services to government, commercial, and NGO clients. Dr. Turpen holds a PhD from the Fletcher School of Law and Diplomacy at Tufts University.