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LAYING THE FOUNDATION FOR NEW AND ADVANCED NUCLEAR REACTORS IN THE UNITED STATES

Committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States

Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

Nuclear and Radiation Studies Board
Division on Earth and Life Studies

National Academies of Sciences, Engineering, and Medicine

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Consensus Study Report

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Vicky Bailey, Anderson Stratton Enterprises
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Tim Taylor, National Center for Construction Education and Research

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report, nor did they see the final draft before its release. The review of this report was overseen by Robert C. Dynes (NAS), University of California, San Diego, and George Apostolakis (NAE), Massachusetts Institute of Technology. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Preface

The world confronts an existential challenge in responding to climate change, resulting in an urgent need to reduce greenhouse gas emissions from all sectors of the economy. At the same time, there is growing concern throughout the world with ensuring energy security. In response, a rapid transition is necessary to reduce dependence on fossil fuels. While there will certainly be increased reliance on renewable energy, other low-carbon technologies will also likely play a significant role. The trajectory for this technology transition is very uncertain.

Nuclear power provides a significant portion of the world's low-carbon electricity, and it is widely recognized that the ongoing contribution from existing nuclear power plants will be essential to achieve carbon-reduction targets over the next decade or longer. Many companies in the United States and around the world are pursuing development of advanced reactor technologies and targeting demonstration and deployment in coming years. The vendors claim that the new designs offer improved safety, lower cost, shorter construction times, and increased operational flexibility over existing reactors. For some technologies, there is also the potential for higher thermal efficiency, higher-temperature operation (opening opportunities for process heat applications), greater fuel utilization, stronger security, improved proliferation resistance, and reduced need for regulatory constraints on deployment. If achieved, these outcomes would be significant, with the result that advanced reactors could be an important component of our energy future.

Because most of the advanced reactors will not complete demonstration until the 2030s, their contribution could only arise in the longer term. The transition of the U.S. economy to use low-carbon energy sources will likely span several decades, and the contribution of various technologies will likely evolve as a result of technical advances, policy actions, economic trade-offs, infrastructure constraints, and many other factors. If advanced reactors are to play an important role, there is a need to consider the uncertainties bearing on future deployment. The uncertainties encompass the evolution of energy policy, comparative economics with other energy technologies, the challenge of building plants on budget and on schedule, future energy demand and the structure of the grid, societal preferences, and the prospect of using nuclear energy for purposes beyond electricity generation. Uncertainties also arise from the need to provide strong assurance of safety and security, regulatory hurdles, international market opportunities, waste disposition, nonproliferation concerns, and the availability of fuel and necessary supply chains. It is important to address many of these uncertainties now to the extent possible to lay a foundation so that advanced reactors can contribute in the future.

Against this backdrop, the National Academies of Sciences, Engineering, and Medicine appointed an ad hoc consensus committee to identify the opportunities and barriers for new nuclear technologies to contribute meaningfully to a low-carbon future (see statement of task in Box 1-1). The committee's work commenced in January 2021 and had to overcome significant challenges in the information-gathering and deliberative phases of its work as a result of the global pandemic. The committee had many information-gathering webinars with experts, countless subgroup discussions, and 14 full committee meetings.

The committee was made up of members with expertise in a variety of different domains, facilitating the response to the wide-ranging scope of our charge. I would like to thank the committee for their enthusiasm, time, effort, and expertise. The congeniality of the group greatly facilitated our efforts. I would also like to thank the National Academies' staff who assisted in our work. They include Kasia Kornecki, Jasmine Bryant, Kyra Howe, Rebecca DeBoer, Catherine Wise, and Jennifer Heimberg.

We are hopeful that our report clarifies the barriers that must be overcome for advanced reactors to play a role in the response to climate change and assists in their resolution.

Richard A. Meserve, *Chair*
Committee on Laying the Foundation for
New and Advanced Reactors in the United States

Summary

Achieving climate goals and enhancing energy security will require a transformation of the energy system and substantial private sector and government investment in a broad portfolio of low-carbon energy technologies over the next several decades.[1] This study, funded by a generous donation to the National Academy of Engineering, and additional funding from the Department of Energy (DOE), identifies the unique opportunities and barriers for one such technology—new and advanced nuclear reactors[2]—to play a role in this transformation and provides recommendations to enable such reactors to contribute meaningfully to a low-carbon future.

For many advanced nuclear reactors, the proposed business opportunities and deployment scenarios are quite different from those of the light water reactors (LWRs) used for electricity production today. Not only do many of these advanced reactors use different technology, but many also offer new deployment scenarios: a variety of sizes and scales to meet various electricity output requirements, non-electric applications of reactor energy output (e.g., process heat), transportable reactors, and factory manufacture of reactor modules, or complete factory manufacture of entire reactors. These innovative ideas are, in part, a response to a rapidly changing electricity ecosystem that is becoming increasingly reliant on variable renewable energy and may need firm power when renewables are unavailable or insufficient to meet grid needs, as well as a recognition of the larger decarbonization challenge for sectors now reliant on fossil fuels.

To realize these scenarios, advanced reactors must succeed in many areas: completing demonstrations of new reactor technologies, verifying new business cases (e.g., non-electric applications), showing improved cost metrics that are competitive with other low-carbon power generation technologies, improving construction and project management compared to current LWR builds, obtaining timely regulatory approval, gaining societal acceptance in host communities, and responding to security and safeguard obligations. Because demonstrations of advanced nuclear designs are not expected until the late 2020s or early 2030s, it may be difficult for new nuclear technologies to contribute significantly until the next few decades. Nonetheless, there is a potential longer-term role for advanced reactors, and overlooking any of the above areas could compromise commercial viability. The race against climate change is both a marathon and a sprint. As is shown in Figure S-1, economy-wide decarbonization will span several decades; projected growth in electricity demand during the 2030s, 2040s, 2050s, and beyond presents important long-term opportunities for advanced nuclear technologies. This summary reflects some of the principal enabling recommendations from the report. Other recommendations are found in the body of the report.

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[1] In order to allow brevity, this summary highlights only some of the recommendations in the report. It sets out the numbering of recommendations as in the body of the report. The full array of recommendations is available in Appendix I.

[2] The study charge is about "new and advanced reactors," a term that includes LWRs that are significantly different from current designs (principally, small modular reactors [SMRs]) and reactors using coolants different from light water (e.g., sodium, molten salts, or helium). The focus of the report is on power reactors, not test or research reactors, or production reactors. "New and advanced reactors" will be abbreviated to "advanced reactors" throughout this report.

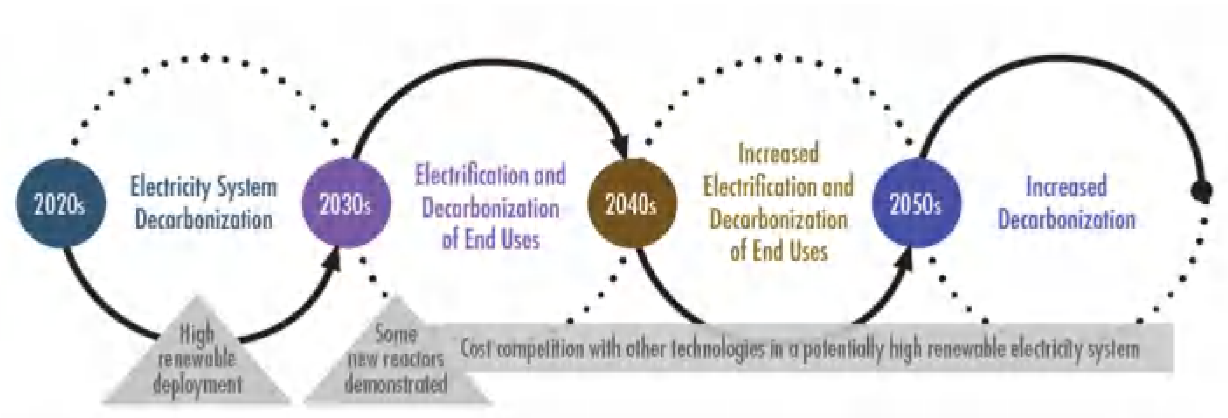

FIGURE S-1 Projected growth in electricity demand during the 2030s, 2040s, 2050s, and beyond presents important long-term opportunities for advanced nuclear technologies.

REACTOR TECHNOLOGIES

Some advanced reactors differ from LWRs used for power production today in terms of size, neutron spectrum, coolant, fuel type, fuel enrichment, and/or outlet temperature. The various advanced reactors under development are at different levels of technological maturity and therefore must confront different technology gaps before wide-scale deployment. More mature concepts—small modular LWRs, small modular sodium-cooled fast reactors (SFRs), small modular high-temperature gas-cooled reactors (HTGRs)—need to address regulatory qualification of unique systems, resolve fuel and supply chain issues, and demonstrate operational performance. SFRs and HTGRs will need to address supply chain and high-assay low-enrichment uranium (HALEU) issues and operational reliability, which have impacted those designs in the past. Less mature concepts—gas-cooled fast reactors (GFRs), fluoride-molten-salt-cooled high-temperature reactors (FHRs), molten-salt-fueled reactors (MSRs), large SFRs—have technology gaps related to viability and performance of key reactor features, including fuel and materials behavior and adequacy of passive safety systems. Increased use of better-performing materials, advanced fuels and high-performance fuel cladding materials, and advanced/additive manufacturing could produce notable improvements in performance and economics. While many of the current concepts plan to move to commercial reactor demonstration with existing materials, optimization of future reactor systems and further improvements in safety, reliability, and economics will require advancements in technology and materials. Focused investment in these issues is necessary to enable these technologies to advance to wider deployment.

> **Recommendation 2-2: The Department of Energy (DOE) should initiate a research program that sets aggressive goals for improving fuels and materials performance. This could take the form of a strategic partnership for research and development involving DOE's Office of Nuclear Energy and Office of Science, the U.S. Nuclear Regulatory Commission, the Electric Power Research Institute, the nuclear industry, national laboratories, and universities. The program should incentivize the use of modern materials science, including access to modern test reactors, to decrease the time to deployment of materials with improved performance and to accelerate the qualification (ASME Section III, Division 5 or equivalent) and understanding of life-limiting degradation processes of a limited number of high-performance structural materials—for example, reactor core materials and cladding.**

THE EVOLVING ELECTRICITY SYSTEM

Increased electrification to enable economy-wide decarbonization presents a significant market opportunity for advanced nuclear generation to serve the grid. While many uncertainties surround the future electricity system, increased electricity demand, greater deployment of distributed resources, increased electrification of end-uses, and the greater application of demand flexibility technologies are expected to increase and change future generation needs. Large growth in renewable generation is expected, but many modeling studies suggest that some firm capacity will be required for lowest-cost and reliable electricity in high-renewable scenarios.[3] While advanced nuclear reactors could fill this need at a variety of scales (from a few megawatts to a gigawatt), many other low-carbon technologies will vie for this opportunity as well. Even in a future with significant variable renewables, the generation of electricity will likely remain the most consequential output from advanced reactors.

Nuclear power's competitiveness to serve projected electricity demand, however, is highly sensitive to cost projections. Recent studies suggest that advanced nuclear will likely be highly competitive if overnight capital costs of $2,000/kWe are achieved, regardless of other conditions. Advanced nuclear could also be competitive for electricity production for overnight capital cost ranges of $4,000–$6,000/kWe if other power system costs are higher than expected (e.g., owing to limited transmission growth or limited materials). Nuclear power could be deployed for reasons other than least cost, such as to maintain optionality, as well as for non-grid nuclear applications even if overnight capital costs are higher than $6,000/kWe. Regulatory reforms, including to wholesale electricity markets, could better capture the value that advanced nuclear reactors could contribute to electricity system reliability and resilience.

CONTROLLING COSTS

The up-front financing costs for developing nuclear reactors are currently higher than those for other energy technologies because of large capital requirements, extended development timelines, and limited financing options. These challenges are being addressed in part by various DOE programs, including the Advanced Reactor Demonstration Program (ARDP), a private–public partnership program to demonstrate new and advanced nuclear technologies, as well as the DOE support centers for nuclear R&D (Gateway for Accelerated Innovation in Nuclear [GAIN], the National Reactor Innovation Center [NRIC], and Nuclear Science User Facilities [NSUF]). While final costs for planned ARDP plants are still uncertain, the level of government funding and vendor matching contributions for the first-of-a-kind (FOAK) demonstrations implies a cost level of 2–2.5 times the $4000–$6000/kWe capital cost threshold. Significant and rapid learning and cost reductions will be necessary when moving from FOAK to nth-of-a-kind (NOAK) to achieve market breakthrough.

In order to ensure the efficient deployment of scarce resources, U.S. federal government programs for advanced nuclear development need better coordination and continuity from early R&D through demonstration and deployment. Programs should include decision points for continuation or termination of funding for specific reactor concepts. A comprehensive set of development phases and milestones, and a clear understanding of commercialization strategy requirements should define all federal funding assistance.

> **Recommendation 4-2: The nuclear industry and the Department of Energy's Office of Nuclear Energy should fully develop a structured, ongoing program to ensure the best performing technologies move rapidly to and through demonstration as measured by technical (testing, reliability), financial (cost, schedule), regulatory, and social acceptance milestones. Concepts that do not meet their milestones in the ordinary course should no**

[3] Firm capacity represents generation that can support system resource adequacy and can be reliably counted on in planning reserves.

longer receive support and newer concepts should be allowed to enter the program in their place.

Recommendation 4-3: Congress and the Department of Energy (DOE) should maintain the Advanced Reactor Demonstration Program (ARDP) concept. DOE should develop a coordinated plan among owner/operators, industry vendors, and the DOE laboratories that supports needed development efforts. The ARDP plan needs to include long-range funding linked to staged milestones; ongoing design, cost, and schedule reviews; and siting and community acceptance reviews. This plan will help DOE downselect among concepts for continued support toward demonstration. A modification in the demonstration schedule that takes a phased (versus concurrent) approach to reactor demonstration may be required. For example, funding would be continued for the first two demonstrations under the ARDP. A second round of demonstrations of designs expected to mature from the current ARDP Risk Reduction for Future Demonstrations award recipients could be funded for demonstration under an "ARDP 2.0" starting thereafter and going into the future.

The commercial deployment of low-carbon energy resources will require substantial investment. To obtain funds at this scale, each project investment must present sufficiently low risk that it can compete with other "ordinary" investments in the public equity and debt markets. Widespread commercial deployment of nuclear reactors will occur only if nuclear power projects can convincingly demonstrate that they can compete in a marketplace with alternatives.

Recommendation 4-4: To enable a cost-competitive market environment for nuclear energy, federal and state governments should provide appropriately tailored financial incentives (extending and perhaps enhancing those provided recently in the Inflation Reduction Act) that industry can use as part of a commercialization plan, consistent with the successful incentives provided to renewables. These tools may vary by state, locality, and market type. Continued evaluation of the recently passed incentives will need assessment to determine their adequacy. The scale of these incentives needs to be sufficient not only to encourage nuclear projects but also the vendors and the supporting supply chains.

NON-ELECTRIC APPLICATIONS

In addition to providing electricity to customers across economic sectors, nuclear power plants can provide heat for industrial processes. Depending on the specific process, electricity and/or heat could be used to power hydrogen production (or associated synfuels), desalination, or district heating. Although the recently passed incentives in the Inflation Reduction Act may or may not be sufficient to encourage nuclear deployment, certain geographic locations, and new demand scenarios (e.g., industrial decarbonization) could create future market opportunities. All of these applications could become important as the chemical, materials, and transportation sectors transition to low-carbon operations, with hydrogen providing perhaps the most credible potential revenue stream owing to its value across all these sectors (particularly as a feedstock for synthetic fuels). Not only might reactors be dedicated to serving non-electric needs, but also owners might opt for hybrid systems (e.g., an industrial park) that can monetize non-electric products when the electricity production from a reactor is not needed to meet grid demand. Engaging in such hybrid operations is not trivial and poses technical and regulatory challenges that must be resolved for each unique deployment paradigm.

Recommendation 5-1: Industrial applications using thermal energy present an important new mission for advanced reactors. Key research and development needs for industrial applications include assessing system integration, operations, safety, community acceptance, market size as a function of varying levels of implicit or explicit carbon price, and regulatory risks, with hydrogen production as a top priority. The Department of Energy, with the support of industry support groups such as the Electric Power Research Institute and the nuclear vendors, should conduct a systematic analysis of system integration, operation, and safety risks to provide investors with realistic models of deployment to inform business cases and work with potential host communities.

PROJECT MANAGEMENT AND CONSTRUCTION

Nuclear projects in the United States and Europe have not been built on budget or on schedule in recent decades. Much of the cost growth does not necessarily arise from the nuclear island, but from the civil works (e.g., concrete or steel structures and balance of plant). This cost growth is owing to a variety of factors, including that a typical U.S. utility company does not have adequate technical and engineering personnel to plan and manage a nuclear construction project.

Recommendation 6-8: While it is vital to demonstrate that advanced reactors are viable from a technical perspective, it is perhaps even more vital to ensure that the overall plant, including the onsite civil work, can be built within cost and schedule constraints. Because it is likely that costs for onsite development will still be a significant contributor to capital cost, and the ~$35 million in Department of Energy (DOE) funding for advanced construction technologies R&D is small in comparison to the hundreds of millions spent on nuclear island technology research, more should be done over an extended period to research technologies that may streamline and reduce costs for this work. DOE should expand its current efforts in R&D for nuclear construction and make these advanced technologies broadly available, including to vendors participating in the the Advanced Reactor Demonstration Program Risk Reduction and ARC20 programs.

Some advanced reactor vendors are considering moving from the traditional “project-based” approach to a “product-based” approach in which the reactor is produced in a factory or shipyard, with the goal of enabling improved schedules, reduced construction risk, associated cost savings, and improved quality. But, even if there are savings with the nuclear components, the challenge of timely and cost-effective construction of the overall civil works remains for deployment scenarios involving extensive on-site construction work.

Recommendation 6-2: Nuclear owner/operators pursuing new nuclear construction should consider the creation of a consortium or joint venture to pursue the construction on behalf of the group, thereby enabling the creation and maintenance of the necessary skilled technical engineering personnel to pursue projects successfully. Alternatively, advanced reactor developers operating within the traditional project delivery model should consider implementing a long-term business relationship, preferably an equity partnership such as a joint venture, or a consortium, with a qualified engineering, procurement, and construction firm experienced in the nuclear industry.

With the above recommendation, the required professional expertise in site-specific planning, engineering design, and execution could be resourced, retained, and deployed for multiple installations of advanced reactors. Efforts should also be made to ensure that lessons from past problems are learned and corrected in new construction, such as a requirement for design completion and peer review before construction. It will also be necessary to develop a skilled workforce with attention to the level of quality assurance that is demanded by nuclear construction.

Recommendation 6-1: In anticipation of the necessary expansion in workforce to support more widespread deployment of nuclear technologies, the Department of Energy should form a cross-department (whole of government) partnership to address workforce needs (spanning the workforce from technician through PhD) that is comparable to initiatives like the multi-agency National Network for Manufacturing Innovation. The program would include the Departments of Labor, Education, Commerce, and State, and would team with labor organizations, industry, regulatory agencies, and other support organizations to identify gaps in critical skills and then fund training and development solutions that will close these gaps in time to support more rapid deployment. In carrying out these efforts, it will be important to take full advantage of existing efforts at commercial nuclear facilities and national laboratories that already have well-established training and workforce development infrastructure in place.

REGULATIONS

The U.S. Nuclear Regulatory Commission (NRC) conducts thorough reviews of reactor applications as part of its obligation to ensure adequate protection of public health, safety, and the environment. With advanced reactor designs, the NRC must adjust a variety of regulatory requirements to accommodate the many differences from existing LWRs. NRC resolution of these issues is required for many new deployment scenarios to be realized. Moreover, establishing the safety case for an advanced reactor will require a thorough verification of safety claims based on detailed analyses founded on experimental data. While the NRC must maintain its overriding commitment to safety, the regulatory process should be made as efficient and flexible as possible if advanced reactors are to be commercialized in the coming decades.

Recommendation 7-1: Advanced reactors will not be commercialized if the regulatory requirements are not adjusted to accommodate their many differences from existing light water reactors. A clear definition of the regulatory requirements for a new technology must be established promptly if timely deployment is to be achieved. The U.S. Nuclear Regulatory Commission (NRC) needs to enhance its capability to resolve the many issues with which it is and will be confronted. In recognition of the urgency for the NRC to prepare now, Congress should provide increased resources on the order of tens of millions of dollars per year to the NRC that are not drawn from fees paid by existing licensees and applicants.

Recommendation 7-4: The U.S. Nuclear Regulatory Commission should expedite the requirements and guidance governing siting and emergency planning zones to enable vendors to determine the restrictions that will govern the deployment of their reactors.

SOCIETAL ACCEPTANCE

Societal acceptance is necessary if new reactors are to play an expanded role in a decarbonized energy system. Social acceptance should be considered early in the design and verification process and continue through project. The industry should engage with a community affected by prospective new construction, hear its needs and concerns, and adjust plans as a result. The effort should reflect an overriding commitment to honesty, early engagement through credible information channels, and genuine effort to develop a partnership. Sociological approaches must become part of the nuclear energy research and development cycle, treated with the same seriousness as technology development. New risk communication strategies—grounded in rigorous social science (going beyond polling) and respect for community apprehensions and desires—could greatly improve the prospects for nuclear deployment in the coming decades. Risk communication strategies that rely exclusively or greatly on the alleged need to remedy the public's lack of knowledge (in other words, the deficit model of science communication) have been tried in the nuclear industry and have failed comprehensively.

Recommendation 8-5: The developers and future owners that represent the advanced nuclear industry should adopt a consent-based approach to siting new facilities. The siting approach will have to be adjusted for a particular place, time, and culture. The nuclear industry should follow the best practices, including (1) a participatory process of site selection; (2) the right for communities to veto or opt out (within agreed-upon limits); (3) some form of compensation granted for affected communities; (4) partial funding for affected communities to conduct independent technical analyses; (5) efforts to develop a partnership to pursue the project between the implementer and local community; and (6) an overriding commitment to honesty. Following these practices will require additional time and financial resources to be allotted to successfully site and construct new nuclear power facilities, and the industry should account for these costs in their plans. The industry should be willing to fully engage with a community, hear its concerns and needs, and be ready to address them, including adjusting plans. While this would raise the likelihood of successful deployment, it is not a guarantee of success. Additionally, the industry, guided by experts in consent-based processes, should capture best siting practices in guidance documents or standards.

SECURITY AND SAFEGUARDS

New deployment scenarios introduce new risks for security (both physical and cyber) and safeguards (to prevent proliferation) that should be addressed early in the reactor design process. To enable the vendors to accommodate these requirements in their designs and in formulating their business plans, early definition of the requirements is essential.

Recommendation 9-1: The modification of the security requirements proposed by the U.S. Nuclear Regulatory Commission (NRC) staff could have significant implications for the design, staffing, and operations of advanced reactors, thereby impacting business plans. Delays in providing clear regulatory guidance may impact capital availability and increases the potential for costly redesign if guidelines do not align with expected modifications to existing protocols. Congress should provide additional funding for NRC evaluation of security guidelines and the NRC should expedite its consideration of the staff proposal and seek to complete the rule making promptly if significant changes are deemed appropriate. In that case, the prompt completion of the associated guidance should also be a high priority.

Sustained, long-term commitments with international partners for development beyond the United States will be important in the planning process. The U.S. government, through DOE's Office of Nuclear Energy, has a range of programs such as ANSWER, GAIN, and NRIC to assist vendors in navigating the challenges to incorporating safety, safeguards, and security into planning and design processes.

Recommendation 9-5: The United States should develop a plan for increased and sustained long-term financial and technical support for capacity building in partner countries, including cost requirements for using U.S. national laboratories and universities as training platforms. This plan should include partnering with U.S. reactor vendors to develop a safety, safeguards, and security "package," where the United States and the vendor could offer customized support to a host country for developing and implementing new safety, safeguards, and security arrangements.

INTERNATIONAL DEPLOYMENT

Many vendors contemplate an international market for their designs. To foster a healthy international market, the U.S. government will need to better equip itself to swiftly negotiate and implement more arrangements for nuclear cooperation with existing and emerging nuclear countries. Although it is not anticipated that significant modifications of export regulations are required to accommodate advanced reactor designs, efforts to increase international harmonization could greatly improve options for export financing. For U.S. vendors to better compete with state-owned or state-financed vendors in the dynamic international energy market, a technically and economically viable product must be established that could then be supported by a robust and reliable source of export credit financing. Most U.S. advanced reactor vendors will not be ready for international commercial deployment until successful demonstrations are completed in the United States and thus will be unlikely to tap export-import bank (EXIM) financing before a new authorization cycle is necessary.

Recommendation 10-2: International nuclear projects by U.S. exporters are likely to require a financing package that reflects a blending of federal grants, loans, and loan guarantees along with various forms of private equity and debt financing. The Executive Branch should work with the private sector to build an effective and competitive financing package for U.S. exporters.

CONCLUSION

In order for advanced reactors to contribute significantly to a decarbonized energy system, there are many challenges that must be overcome. Their resolution requires sustained effort and robust financial support by the Congress, various departments of the U.S. government (especially the Department of Energy and the U.S. Nuclear Regulatory Commission), the nuclear industry, and the financial community. Given the urgency of the need to respond to climate change, it is important to seek the prompt resolution of issues associated with commercialization of low-carbon technologies.

1

Introduction

Climate change presents an existential threat, demanding massive worldwide reductions in the emissions of greenhouse gases. Mitigating this threat will require a continuing evolution in our energy system over the coming decades with an increasing reliance on low-carbon energy sources. Nuclear power could be important in this transition. But the role for nuclear power, as with many other energy technologies, remains uncertain as to its extent and timing. This report will explore the challenges associated with the deployment of new and advanced reactors,[1] identify requirements for success, and make recommendations to lay a foundation for a future in which new and advanced reactors contribute to the future energy mix. The committee's charge is set out in Box 1-1.

The U.S. fleet of commercial nuclear power plants (NPPs) today consists of large light water reactors (LWRs). Proponents of new and advanced reactor technologies claim lower costs, shorter construction times, increased safety, greater reliability, increased operational flexibility, and, for non-LWR type reactors, higher thermal efficiency, greater fuel utilization (allowing extended operation between refueling outages), improved waste characteristics (reducing the spent fuel challenge), higher temperature operation (opening new opportunities for process heat), greater proliferation resistance, and reduced regulatory constraints on deployment. These outcomes would be significant, but whether these potential benefits can be realized is uncertain and will depend on many considerations. Uncertainties surround comparative economics with other energy technologies, future demand for electricity and the structure of the grid, the prospects for applications beyond electricity generation, assurance of safety, regulatory hurdles, societal preferences, international market opportunities,[2] waste disposition, security, project management, supply chains, nonproliferation, and many more.

Although this study acknowledges that expanded utilization of nuclear power presents formidable challenges, the important opportunities provided by advanced reactors warrant exploration. The current fleet of nuclear reactors already contributes significantly to low-carbon power generation, and many studies show that the continued operation of existing plants is essential for meeting near-term decarbonization targets (IEA 2022).[3] Nuclear power can assuredly be expanded to provide reliable low-carbon power and process heat if society should so choose. Given the growing recognition of the devastating impacts of climate change, the barriers to technologies that can contribute to a low-carbon future, including nuclear power, should be addressed and, if possible, overcome.

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[1] The study charge is about "new and advanced reactors," a term that includes LWRs that are significantly different from current designs (principally, small modular reactors [SMRs]) and reactors using coolants different from light water (e.g., sodium, molten salts, or helium). The focus of the report is on power reactors, not test or research reactors, or production reactors. "New and advanced reactors" will be abbreviated to "advanced reactors" throughout this report.

[2] The committee's charge does not explicitly include commercialization outside the United States, but the topic is discussed because domestic commercialization may depend on the availability of international markets.

[3] In light of the importance of existing nuclear plants in meeting carbon targets, the Bipartisan Infrastructure Law provides $6 billion in subsidies for eligible existing plants in order to facilitate their continued operation. The Inflation Reduction Act (IRA) also includes a production tax credit of up to $15 per MWh for electricity produced by plants meeting certain labor and wage requirements.

BOX 1-1
Statement of Task

The National Academies of Sciences, Engineering, and Medicine will appoint an ad hoc committee of experts to identify opportunities and barriers to the commercialization of new and advanced nuclear reactor technologies in the United States over the next 30 years as part of a decarbonization strategy. Specific topics the committee will examine include

- The research, development, and demonstration needed for new and advanced nuclear reactor technologies to reach commercial readiness, the potential for leveraging technological developments outside the nuclear energy sector, and the manufacturing, construction, financial, societal, and other barriers associated with their deployment;
- The operational characteristics of these technologies, including their implications for safety, security, and non-proliferation, as well as their interaction with other low-carbon generation and storage resources that may be relevant to a changing electricity system;
- The economic, regulatory, and business challenges associated with commercialization of these technologies;
- The implications of these technologies for the front- and back-end of the fuel cycle;
- The viability of these technologies in applications outside the electricity sector, for example in desalination, water and wastewater treatment, hydrogen production, or process heat;
- The role of the U.S. government in sponsoring the development and commercialization of new and advanced nuclear reactor technologies to provide clean energy, to address national-security and nonproliferation goals, or to assist in nuclear exports; and
- The future workforce and educational needs to support the research, development, and deployment of these technologies.

THE CONTEXT

The Current State of Nuclear Power in the United States

There are 442 NPPs in operation across the globe. Nuclear energy accounts for ~20 percent of the electricity produced in the United States, ~25 percent in Europe, and ~10 percent worldwide, and it is the largest low-carbon resource in the United States, generating just under half of all low-carbon electricity (EIA 2021).

NPPs in the United States have a combined capacity of 95.5 GWe generated at 54 NPPs (92 reactor units). All of these reactors are LWRs, and most of the later additions to the fleet are large (roughly 1 GWe). They use uranium oxide as fuel, enriched to about 5 percent ^{235}U, and ordinary water as both a coolant and moderator, with traditional Rankine steam-cycle power conversion systems. The average age of the current fleet of reactors is about 40 years (the term allowed in their initial licenses), and nearly all the plants have had their operating licenses extended to 60 years.[4] Over the past decade, some nuclear retirements (as well as many retirements of coal-fired generation) have occurred as a result of the low cost of natural-gas-fired electricity generation (EIA 2022). In the aftermath of the Russian invasion of Ukraine, however, global gas shortages and volatile gas prices are occurring and there is an increased focus on energy security. The continued expansion of electricity generation using natural gas is somewhat uncertain. At the same time, electricity demand is projected to grow 50 percent by 2050 (EIA 2019), raising the important question of what generation technologies will meet this expanded demand.

[4] Subsequent renewed licenses to 80 years have been granted for six units (subject in some cases to completion of environmental review requirements) and other applications are under review and are anticipated. See https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html#complete.

In 2009, the National Research Council published *America's Energy Future*, a report that assessed the status of energy-supply and end-use technologies over the next two decades (National Research Council 2009). At the time, the only types of new nuclear plants being commercially considered were evolutionary modifications of the original operating fleet—large (~1 GWe) LWRs. The report indicated that commercial deployment of such reactors would depend in large part on the economics of plant construction: if new plants built between 2009 and 2020 met cost and schedule requirements, the report predicted that others could follow. Two projects were undertaken during that timeframe, and they have *far exceeded* cost and schedule targets.[5] Consequently, there are no current proposals in the United States for the construction of additional large LWRs, calling into question whether additional gigawatt-scale LWRs will be built in the United States.

Since the publication of *America's Energy Future*, the awareness of anthropogenic climate change has grown, leading to promises by the United States and other countries to reduce greenhouse gas emissions dramatically in the years ahead. President Biden has committed the United States to a 50–52 percent reduction in greenhouse gas emissions from 2005 levels by 2030 and net-zero emissions across the economy by no later than 2050. Other countries have made similarly dramatic pledges. The achievement of these commitments will require significant changes in the entire energy infrastructure.

Only a portion of total electricity generation in the United States is provided by low-carbon sources: 18.9 percent comes from the fleet of NPPs, 13.8 percent from solar and wind ("variable renewables"), and 6.3 percent from hydropower. Most of the remainder comes from fossil sources. There is a strong political and economic consensus in the United States that continued and significant growth of variable renewables will be important, encouraged by the cost reductions that have been achieved and the potential for further reductions. But, as discussed below, there may be limitations to relying on deployment of renewables; other technologies, including nuclear power, could be important complements to renewables in our future energy supply.

Decarbonization and the Changing Electricity System

Decarbonizing our entire economy (including the electricity, industrial, transportation, agriculture, commercial and residential buildings sectors) will require increased electrification and concomitant expansion of the electricity system to meet a wider set of demands than today (e.g., electric vehicle charging), making low-carbon electricity generation sources a particular focus in the efforts to reduce carbon emissions. Various electricity generation technologies have differing life cycle greenhouse gas (GHG) emissions, as shown by Figure 1-1. Nuclear power generation has very low life cycle GHG emissions[6] and the low-carbon character of nuclear power is a key factor that motivates this study.

[5] One project (two reactor units), Vogtle NPP in Georgia, has doubled in cost and commissioning has been delayed about 5 years. Another project (two reactor units), VC Summer NPP in South Carolina, was cancelled after cost overruns became unmanageable.

[6] The term "life cycle GHG emissions" refers to the aggregate quantity of greenhouse emissions arising from the full life cycle, including all stages of fuel production, the construction, operation, and decommissioning of the power plant, as well as back-end fuel management.

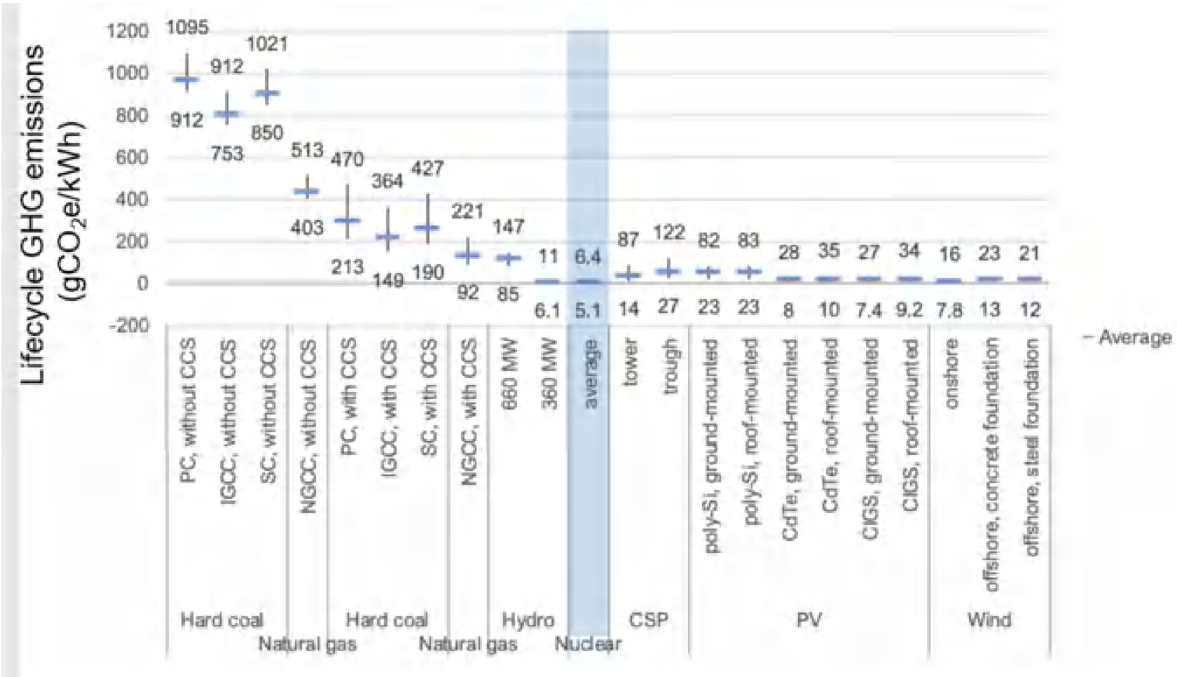

FIGURE 1-1 Life cycle GHG emissions, in g CO_2-equivalent per kWh, with regional variation, 2020. SOURCE: From *Life Cycle Assessment of Electricity Generation Options*, by United Nations Economic Commission for Europe, © 2021 United Nations. Reprinted with the permission of the United Nations.

While variable generation, such as wind and solar, will likely become central to electricity systems, it does not provide a universal or assured solution. There is a need for firm capacity when variable renewable generation is unavailable or insufficient to meet grid needs. Moreover, there may be constraints on renewables as a result of land-use limitations,[7] the availability of rare minerals needed for their manufacture, regional differences in renewable resource availability, and the formidable challenge of a significant expansion of our transmission system to bring power from remote renewable sites to load.[8] Other technologies in addition to nuclear power that could play a role in this evolving system include energy storage;[9] fossil plants with carbon capture, utilization, or sequestration (CCUS); and geothermal energy and non-traditional hydropower—all of which carry their own costs, risks, limitations, and uncertainties.

In fact, there are many pathways by which the decarbonization goal could be reached with widely varying costs and constraints, but many global studies contemplate an important role for nuclear power. The International Atomic Energy Agency recently concluded that “nuclear is well placed to help decarbonize electricity supply” and that “nuclear power plays a significant role in a secure global pathway to net zero [carbon emissions].” In 2018, the Intergovernmental Panel on Climate Change considered 90 pathways to limit global average temperature warming to 1.5ºC and found that, on average, the pathways

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[7] For example, the prevalence and stringency of ordinances restricting the deployment of wind generation is increasing across the United States, particularly in the Midwest. In Iowa, 16 or 19 counties have adopted strict restrictions in the past 4 years. See Clearpath, 2022, “Hawkeye State Headwinds: A Case Study of Local Opposition and Siting Challenges for Large Scale Wind Development in Iowa,” https://static.clearpath.org/2022/07/hawkeye-headwinds-report-large.pdf.

[8] The cost of the expansion of the transmission system has been estimated at $360 billion (Larson et al. 2021).

[9] Storage might be provided by chemical means in batteries or in low-carbon synthetic fuels, by potential energy (e.g., pumped storage between water reservoirs at different elevations or compressed air at high pressures), or as high-temperature heat (e.g., by storage of high-temperature salt).

require nuclear power across the globe to reach 1,160 GWe capacity by 2050, up from 394 GWe in 2020. (Nuclear Energy Agency 2022). Figure 1-2 sets out some recent estimates of predicted nuclear growth through 2050, yet caution is warranted in reviewing these projections, as they are dependent on a variety of assumptions. Moreover, analyses about deployment worldwide do not necessarily reflect the energy path for the United States.

Organization	Scenario	Climate target	Nuclear Innovation	Description	Role of nuclear energy by 2050	
					Capacity (GW)	Nuclear Growth (2020-2050)
IAEA (2021b)	High Scenario	2°C	Not included	Conservative projections based on current plans and industry announcements.	792	98%
IEA (2021c)	Net Zero Scenario (NZE)	1.5°C	Not included in the quantitative model, although the potential of HTGR and nuclear heat are acknowledged in the report narrative	Conservative nuclear capacity estimates. NZE projects 100 gigawatts more nuclear energy than the IEA sustainable development scenario.	812	103%
Shell (2021)	Sky 1.5 Scenario	1.5°C	Not specified	Ambitious estimates based on massive investments to boost economic recovery and build resilient energy systems.	1 043	160%
IIASA (2021)	Divergent Net Zero Scenario	1.5°C	Not specified	Ambitious projections required to compensate for delayed actions and divergent climate policies.	1 232	208%
Bloomberg NEF (2021)	New Energy Outlook Red Scenario	1.5°C	Explicit focus on SMRs and nuclear hydrogen	Highly ambitious nuclear pathway with large-scale deployment of nuclear innovation.	7 080	1670%

Many pathways require global installed nuclear capacity to grow significantly, often more than doubling by 2050

FIGURE 1-2 Nuclear in emission reductions pathways.
SOURCE: Nuclear Energy Agency, 2022, *Meeting Climate Change Targets: The Role of Nuclear Energy*, Paris: OECD Publishing, https://www.oecd-nea.org/jcms/pl_69396/meeting-climate-change-targets-the-role-of-nuclear-energy.

The electric power system in the United States is undergoing a sweeping transition in parallel with the movement to low-carbon generation. The most prominent challenges include (1) the speed and scale of new infrastructure needed to decarbonize and meet higher demand; (2) finding economic means to provide firm capacity when renewable generation is not available or is insufficient; (3) the growth of decentralized generation and residential and commercial energy management models arising from variable tariffs, smart metering, demand response, and microgrids; and (4) increased efforts to electrify transportation, commercial and residential buildings, and industrial processes. As responses to these challenges are being developed, the threats facing the aging electric power system are becoming more acute, including those arising from the extreme natural events associated with climate change and the threat of physical or cyber sabotage. At the same time, the regulations and market rules governing the electricity system are evolving in uncertain ways. As a result, there is uncertainty surrounding nearly every aspect of our electricity system.

Further complicating decarbonization efforts, electricity generation constitutes only about 30 percent of carbon emissions, and some sectors of the economy cannot be directly decarbonized by electrification. The strategy to achieve a low-carbon future must extend beyond electricity to consider the means by which to meet a much wider set of energy needs. For example, the decarbonization of the transportation sector would be furthered by the wide-scale deployment of electric vehicles, but likely will also require low-carbon liquid fuels for heavy trucks, rail, aircraft, and marine shipping. The continued need for liquid fuels might be met by combining hydrogen produced by electrolysis of water with carbon dioxide to manufacture synfuels or with nitrogen to produce ammonia. Heat from low-carbon sources might be substituted for heat from fossil fuels for industrial processes that do not lend themselves to electrification. Nuclear power, along with other technologies, can be deployed to meet energy needs beyond electricity production.

The optimal balance among the various possible energy sources to meet future demand in a low-carbon energy system is unclear. Indeed, regional differences in the optimal balance are to be expected given resource availability and other factors. And the optimal balance in one period will not necessarily be optimal in other periods because of technical, economic, legal, social, environmental, or policy developments.

Moreover, in evaluating the opportunity for nuclear power to address climate change, three crucial timelines must be considered together: the timeline for deployment of low-carbon technologies, the timeline for decarbonization of end-uses, and the timeline to develop and demonstrate new clean energy technologies. As noted above, large LWRs using existing technology will contribute in the near term, but there is little enthusiasm today for their deployment in new construction in the United States.[10] Because demonstrations of new and advanced nuclear designs are not expected until the late 2020s or early 2030s, it may be difficult for new nuclear technologies to contribute significantly until the next few decades. Nonetheless, there is a potential longer-term role for advanced reactors. Electricity demand will grow, the costs and benefits of various technologies may change, capital stock will turn over and need to be replaced (providing the opportunity for technology substitutions), and decarbonization of buildings, industry, and transportation will continue to be targets for decades to come (Figure 1-3). While there is

[10] The picture is different outside the United States. About 55 power reactors are currently being constructed in 19 countries and most of these reactors are large LWRs (1 GWe or larger).

urgency in focusing on short-term solutions for decarbonization, advanced reactors could play an important role in coming decades.

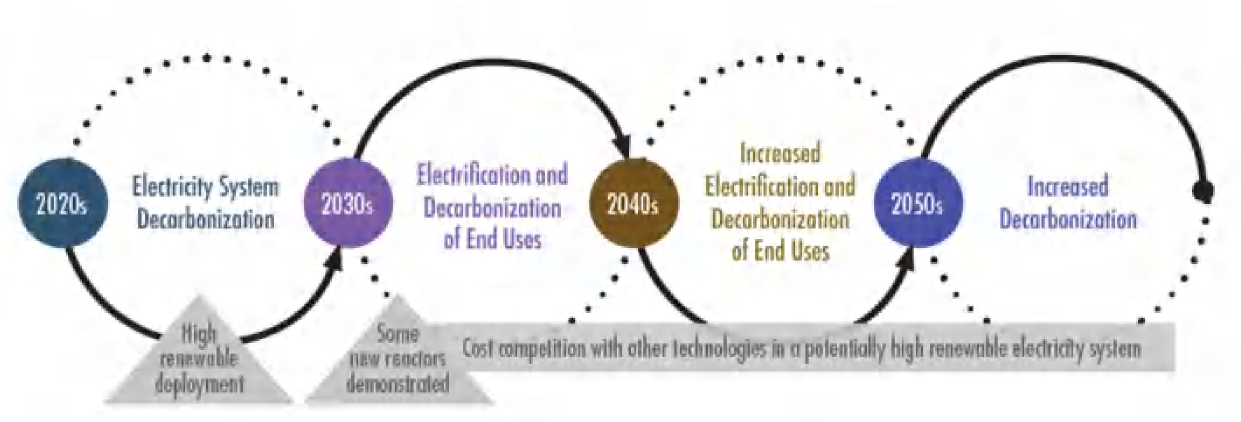

FIGURE 1-3 Projected growth in electricity demand during the 2030s, 2040s, 2050s, and beyond presents important long-term opportunities for advanced nuclear technologies.

Finding 1-1: The energy system must undergo radical change at unprecedented speed to meet the existential challenge of climate change. Many technologies with a variety of different attributes can and will contribute to the evolution of the energy system, and the barriers to technologies that can contribute to a low-carbon future should be addressed and, if possible, overcome. Nuclear has the benefits of a small land footprint and reliable availability, but historically, it has had drawbacks related to high up-front development and capital costs and fuel-cycle associated risks.

Finding 1-2: The earliest timeframe for U.S. commercialization of some advanced nuclear reactors will be in the mid-2030s, and only if the challenges identified in this report are addressed in this decade. Yet, the race against climate change is both a marathon and a sprint. Growth in electricity demand and the need to achieve economy-wide decarbonization over the coming several decades present important long-term opportunities for advanced nuclear technologies.

NEW TECHNOLOGY DEPLOYMENT SCENARIOS

A variety of vendors are pursuing innovative reactor designs in anticipation of a substantial future market in the United States and abroad and in response to the potential needs of an evolving energy system. The vendors offer a variety of deployment scenarios for these new technologies:

- Deploying small modular reactors for electricity production. The smaller size may enable the manufacture of a major portion of the plant components (or in some cases entire systems) in a controlled factory setting, which could improve quality and reduce on-site construction activity and costs. Multiple modules of these reactors could be located on the same site to obtain the power capacity required by a customer. Alternatively, installation of these reactor modules could be staggered over time to complement growing demand or an owner-operator’s financing ability.
- Repurposing existing fossil generation sites (e.g., coal plants) with new nuclear generation to benefit from existing transmission infrastructure, cooling capability, and possibly portions of the existing plant outside the nuclear island (e.g., turbine-generators).
- Combining electricity production with thermal energy storage, thereby providing flexible operation.

- Producing high-temperature heat for industry, such as chemical processing or hydrogen production.
- Producing low-temperature heat for district heating, desalination, or agriculture.
- Combining off-grid electricity and district heating.
- Providing dedicated electricity supply to an industrial partner (rather than providing power to a bulk power grid).
- Using microreactors (1–10 MWe) for remote sites, electric vehicle charging, ancillary services at key grid nodes, or even as a primary source of electricity in a reconfigured grid.
- Providing transportable small reactors or microreactors to meet emergency needs.
- Deploying reactors that are moored or located offshore from load centers, thereby enabling efficient shipyard construction and alleviating siting restrictions.
- Using nuclear reactors for marine propulsion.
- Providing reliable and resilient onsite power for military bases.

Demonstration plants and pilot projects will need to be built for novel designs and novel deployment paradigms before wide commercial exploitation is possible. As described in more detail in Chapter 4, the U.S. Congress has allocated significant funds over the past decade to support advanced reactor concepts in partnership with the private sector and has established several new programs to nurture new reactor technology (Box 1-2). The traditional nuclear deployment strategy has depended on the conduct of significant government-funded R&D before passing a new concept to industry for possible commercial deployment (e.g., *Next Generation Nuclear Plant of the Early 2000s*; see NRC 2021a). To meet aggressive deployment scenarios in the coming decades, a more comprehensive approach is required. Congress has recognized this reality in the Inflation Reduction Act (IRA); it provides incentives for clean energy technologies (production and investment tax credits), including nuclear power, that are aimed at nurturing commercialization.

Even with significant government support, a credible and commercially viable nuclear power technology requires

- Developing a business case that shows a competitive advantage over alternatives. For example, a nuclear plant to provide high-temperature heat would have to outperform natural gas with carbon capture and storage or solar-to-heat systems.
- Convincing investors to finance and build the needed supply chains and factories. A current example is the need for high-assay low-enriched uranium (HALEU) desired by many advanced reactor vendors.
- Completing regulatory approvals in a timely manner for products that are new to the regulator.
- Attaining community acceptance for deploying nuclear reactors, both in traditional ways and in first-of-a-kind deployment scenarios (e.g., microreactors as part of a distributed network of electric vehicle charging stations).

Many of the proposed new nuclear deployment paradigms would entail novel system integration risks, and both the nuclear plants and the broader systems will need to be evaluated from technical and economic perspectives.

Reactor vendors have taken different approaches to meet the product development, supply-chain creation, regulatory approval, and community acceptance milestones. Four examples are presented in Box 1-3: (1) NuScale has sought to minimize changes from already approved LWR technology; (2) Oklo has chosen to move to very small reactor sizes; (3) TerraPower has chosen to pursue an advanced reactor that has been explored extensively in the past; and (4) Kairos Power seeks to pursue an advanced reactor with which there is limited experience. These were selected because they reflect a range of different development models, not because they exhaust the deployment opportunities of possible interest.

BOX 1-2
List of New Programs Aimed to Accelerate Deployment of Advanced Reactor Concepts

- Nuclear Science User Facilities (NSUF), which provide access to national laboratory and university capabilities for fuels and materials development (NSUF n.d.).
- Gateway for Accelerated Innovation in Nuclear (GAIN), which provides access to national laboratory R&D capabilities "to provide the nuclear community with access to the technical, regulatory, and financial support necessary to move innovative nuclear energy technologies toward commercialization" (GAIN n.d.).
- U.S. Industry Opportunities for Advanced Nuclear Technology Development (DOE 2021) "cost-shared projects to develop innovative industry-driven reactor designs and technologies to advance nuclear power in America," which includes regulatory assistance.
- National Reactor Innovation Center (NRIC), which provides support to demonstrate advanced reactors (NRIC n.d.).
- Various nuclear energy programs from the Advanced Research Projects–Energy (ARPA-E) that provide funding targeted at solving key barriers to commercialization such as designing optimal operations and maintenance.
- Advanced Reactor Demonstration Program (ARDP), which aims to speed the demonstration of advanced reactors through cost-shared partnerships with U.S. industry (DOE-NE n.d.).
- Loan Program Office (LPO), which provides debt financing for the commercial deployment of large-scale energy projects.

BOX 1-3
Industry Examples of New Development/Deployment Models

NuScale Power

The Utah Associated Municipal Power Systems' (UAMPS's) Carbon Free Power Project has stated publicly that its first NuScale Power Module will be deployed in 2029 with subsequent modules coming online for full power operation in 2030 (NuScale Power 2022a). The first NuScale plant, with six 77 MWe modules, will be built at the Idaho National Laboratory (INL). NuScale has chosen to use as much proven LWR technology as possible to decrease the time for regulatory approval and deployment. The reactor does not use HALEU fuel.

For NuScale, transitioning from the first commercial demonstration plant in Idaho to broad commercial deployment will require finding deployment opportunities outside the controlled environment at a DOE site; proving that deployments of a modular plant are desirable to commercial customers and the associated communities; obtaining necessary regulatory approvals, including approvals for sales in countries outside the United States; and building the manufacturing capacity and supply chains for production of multiple modules beyond NuScale's projected 2028 capacity of 12 modules per year.

Oklo Aurora

Oklo is designing a microreactor, called Aurora, with an expected capacity of 1.5 MWe. Oklo envisions deployment of Aurora reactors to provide electricity and/or heat to potential customers, including in remote regions where the price of electricity is high and at industrial sites or on university campuses.

Oklo has received a Site Use Permit from DOE to build its Aurora plant as a demonstration at INL (Birch 2020). It has also piloted an entirely new application structure with the NRC, which is not based on the LWR-centric Standard Review Plan, by applying for a Combined License for the Idaho site (Birch 2020). In January 2022, the NRC terminated the review of the application based on Oklo's failure to provide requested information (NRC 2022c). Oklo intends to reapply and has expressed confidence to the committee that its application will be approved (Oklo 2022).

To transition to wide-scale commercial deployment, Oklo will need to complete regulatory approval; find deployment opportunities outside the controlled environment at a DOE site; prove the reliability of a sodium-cooled system; obtain community acceptance across a wide number of new deployment scenarios; prove that a strategy based on multiples of very small reactors is cost effective; and build out the needed manufacturing and supply chains. There is also a need to create a source of HALEU fuel for concepts such as the Oklo Aurora.

TerraPower Natrium

TerraPower, with major technical support from GE Hitachi Nuclear Energy and Bechtel, is working to deploy the Natrium concept, a 345 MWe sodium-cooled fast reactor technology, combined with an integrated thermal storage system using molten salt (TerraPower 2021b). The storage system is sized to allow 500 MWe for a maximum of 5.5 hours. This flexibility is intended to make Natrium plants capable of rapid load following while running the reactor at constant power. The concept has particular value to utility systems supplied by a significant fraction of renewable energy. The first demonstration is planned at a retiring coal plant in Kemmerer, Wyoming, where some existing infrastructure will be repurposed (Yurman 2021). TerraPower plans to have an operating plant in 2030 (WNN 2021b). Members of the demonstration project team include nearly a dozen additional companies, universities, and national laboratory partners (WNN 2021b). The Natrium concept is funded in part through DOE's Advanced Reactor Demonstration Program (ARDP) and receives advice and support from an advisory committee with more than two dozen utilities and energy users, including PacifiCorp, Duke Energy, and Energy Northwest. The reactor requires the use of HALEU fuel.

To transition to wide-scale commercial deployment, TerraPower will need to complete regulatory approval for Natrium; find deployment opportunities outside of the first coal plant retrofit; prove the ability to operate a sodium-cooled system with a high-capacity factor; obtain community acceptance across a wide number of new deployment scenarios; and prove that the concept is economically competitive. There is also a need to create a source of HALEU fuel for concepts such as the TerraPower Natrium reactor.

Kairos Power

Kairos Power is developing a fluoride salt-cooled high-temperature thermal reactor (FHR) that uses TRISO particle fuel technology in combination with a liquid fluoride-lithium-beryllium (Flibe) salt coolant at high temperatures and ambient pressure. The Kairos development approach is unique, where at each stage of the design and development an iterative process of "design, build, and test" is employed in order to obtain key test data that can improve the eventual commercial reactor design. The company has just commissioned a non-nuclear facility in New Mexico dedicated to test activities for key components in its Engineering Testing Unit—a major hardware demonstration that will perform integrated Flibe coolant testing as well as tests of a selected set of safety systems components. Kairos has also applied to the NRC for a construction permit for its Hermes low-power test reactor, which will demonstrate Kairos Power's ability to deliver low-cost nuclear heat. Hermes will be located in Oak Ridge, Tennessee, and is the next key milestone in this iterative design-development approach. Kairos's plan is to use the experience gained from Hermes to support the development of the commercial-scale non-nuclear integrated test facility, followed shortly after by deployment of KP-X, a 140 MWe commercial reactor. To transition to wide-scale commercial deployment, Kairos will need to find deployment opportunities and customers; prove the ability to operate a Flibe salt-coolant reactor with a high-capacity factor; obtain community acceptance across a wide number of new deployment scenarios; and prove that the concept is economically competitive. There is also a need to create a source of HALEU fuel for concepts such as the KP-X reactor.

REPORT ROADMAP

Each chapter in this report focuses on a specific challenge area that could constrain widespread and timely commercialization of new and advanced nuclear reactors. The chapters are organized in the order below, and each provides recommendations on how to overcome the identified obstacles by outlining the success requirements for each challenge area. Below is a roadmap and summary of each of these challenge areas.

Technology. While the current LWRs have an excellent record of safety, major accidents like that at Fukushima-Daiichi have suggested that future NPP designs need to be safer than existing plants (including stronger capacity to deal with external hazards), and less dependent on operator actions and active safety systems. These considerations have increased interest in smaller nuclear plant designs that incorporate advanced technologies and improved safety features, as well as lower unit costs. While there is extensive experience with some of the advanced technologies that vendors are pursuing, the designs are at various levels of technical maturity. Chapter 2 describes the various technologies, assesses the safety and technical gaps that must be addressed for the designs to be ready for demonstration and possible deployment, and describes the efforts that are under way to fill the gaps.

Evolution of the grid. The National Academies recently completed a comprehensive assessment of the future of the electric grid in the United States (NASEM 2021), which demonstrates that significant change is occurring and anticipates continued changes for several decades. Demand for electricity will likely grow along with the need for decarbonization. A suite of low-carbon power-generation technologies has experienced high growth rates and concomitant cost reductions. Customer expectations for resiliency, affordability, and equity are evolving. The grid's regulatory framework is evolving both to satisfy these expectations and to capture different value streams. Chapter 3 describes changes to the grid and its customers that affect all power suppliers, including nuclear vendors.

Economics. Although economics will not be the sole determinant of the makeup of the future energy system, it is perhaps the largest challenge to the commercial success of advanced reactors. A variety of studies have examined the mixture of generation technologies that present the lowest overall economic cost, and most indicate that the optimum mixture includes a significant component of nuclear power in a carbon-constrained world *if cost targets for advanced reactors are achieved*. Chapter 4 describes the implications of cost projections for various combinations of generation technologies, the supply chain requirements for various deployment levels, government programs to facilitate the demonstration of advanced nuclear technologies, and the policies that may be necessary to encourage their wide-scale commercial deployment.

Nuclear power beyond electricity. Chapter 5 describes the alternative applications for nuclear power beyond electricity production—industrial heat, hydrogen and synfuel production, district heating, and desalination. Of these, hydrogen production using high-temperature advanced nuclear reactors is perhaps the most promising. Such applications may be important in their own right and as a means to enable the economic deployment of nuclear plants on grids with substantial reliance on variable renewables. That is, at times when the output of the nuclear plant is not needed to meet grid needs, the output could be used for other purposes.

Project management. The recent experience of NPP construction in many developed countries has not been encouraging; it is characterized by delays in completion of construction and significant cost overruns. Depending on the plant, capital cost[11] can account for as much as 80 percent of the cost of energy from an NPP, with the remainder of the cost typically divided between operation and maintenance costs (15 percent) and fuel costs (5 percent). In light of this fact, achieving cost targets for nuclear energy depends highly on effective and efficient project management and on a capable and skilled workforce to construct the plants. Factory or shipyard manufacturing to enable "product-based" deployment has the potential to reduce costs but has yet to be demonstrated for NPP construction. Chapter 6 explains that lessons from past project and construction management failures must be learned and overcome if NPPs are to play a significant role in the future.

U.S. regulation. NPPs are subject to extensive regulatory oversight by the U.S. Nuclear Regulatory Commission (NRC) to ensure protection of the public health and safety and of the common defense and security. The existing system is understandably tailored to address issues associated with

[11] Capital cost refers to the cost to build the power plant. Those costs are then recovered over the life of the plant from revenue from the sale of power.

LWRs. But, given that many vendors are pursuing advanced reactors that are employ technology very different from existing LWRs, the regulatory requirements must change to accommodate them. Because the business case for an advanced reactor must be premised on an understanding of the regulatory environment in which the plant will be licensed and operated, unknown regulatory requirements present an obstacle for commercial deployment. Chapter 7 explains that regulators need to evaluate new risks as well as the ways that vendors plan to prevent or mitigate them, and vendors need to understand the potential limits of the applications of their technologies that arise from regulatory requirements. While the NRC has shown it is prepared to be flexible and to address new safety issues, its capacity will have to be greatly expanded to deal with the regulatory challenges that advanced reactors present in a timely fashion.

Societal acceptance. Nuclear power has provoked public controversy and opposition. Chapter 8 addresses the societal challenges implicated in the deployment of reactors of any type and outlines the myriad economic, social, behavioral, and political realities that affect public attitudes of the technology. At the end of the day, societal acceptance is an essential element for widespread deployment of any energy technology. Although growing concern for climate change may be prompting changes in attitudes about nuclear power,[12] best practices for community engagement and risk communication should nonetheless be pursued to ensure societal support.

Security and safeguards. NPPs are required to have a capability to withstand a physical attack by terrorists and to avoid cyber vulnerabilities. Licensees in non-nuclear weapons states also have the obligation to establish monitoring and surveillance equipment to ensure that weapons-usable nuclear material is not diverted, subject to inspection and oversight by the International Atomic Energy Agency (IAEA).[13] Chapter 9 explains the security and safeguards challenges associated with advanced reactors.

International markets. The global market for new electricity capacity could be substantial as countries develop economically and their needs for electricity grow. Many prospective countries currently do not have the regulatory or commercial infrastructure necessary for safe and secure operation of NPPs and that infrastructure must be developed. In order for a U.S. vendor to participate in a foreign market, there must be an agreement for cooperation (a “123 Agreement”) between the United States and the recipient country. Establishing such an agreement can take many years, and challenges arising from export requirements and financing must also be overcome. Chapter 10 explains that the United States will forgo economic opportunities if it does not seek to compete in the international market; indeed, international sales may prove essential for those U.S. vendors that seek to achieve cost targets through serial production of a large number of units. Moreover, the capacity of the United States to influence the international system for safety, security, and safeguards may wane if it does not pursue nuclear power at home or participate in the international market.[14]

Fuel cycle issues. One significant barrier to increased reliance on nuclear power is the failure to develop repositories for the disposal of spent fuel and high-level waste. Progress has been made in a few other countries (e.g., Finland and Sweden), but not in the United States. Spent fuel in the United States is safely stored at reactor sites in spent fuel pools and in dry-cask storage, but this clearly is not a solution for the long term. Moreover, many of the advanced reactors are pursuing the development and deployment of new fuel cycles, raising economic, safety, security, and safeguards issues beyond those presented by the reactors themselves. Although issues associated with cost uncertainty arising from the

[12] Restrictions on the construction of new nuclear power facilities existed in 13 states, but West Virginia, Kentucky, Montana, and Wisconsin have recently ended these restrictions and several other states are considering a change in policy (Tony 2022). A recent study by MIT and Stanford researchers on the adverse climate impacts of the closure of the Diablo Canyon plant has caused California to encourage the plant’s continued operation (Aborn et al. 2021; Save Clean Energy 2022). At the same time, energy security concerns arising from the Russian invasion in Ukraine are causing several European countries to reconsider their policies governing nuclear power.

[13] The United States is recognized as a weapons state and no U.S. reactors are subject to IAEA safeguards requirements.

[14] The absence of a commercial nuclear power industry in the United States would also have implications for the U.S. Navy. The providers of nuclear-quality components and services to the Navy also rely on the market provided by the commercial nuclear industry. See Energy Futures Initiative (2017).

fuel cycle are discussed in Chapter 4, other fuel cycle and waste issues associated with advanced reactors are addressed in a separate National Academies study (NASEM 2022) and are not encompassed in this report. The committee notes that these issues must also be considered as an aspect of reliance on nuclear power.

> Finding 1-3: In order for advanced reactors to contribute significantly to a decarbonized energy system, there are many challenges that must be overcome. Their resolution requires sustained effort and robust financial support by the Congress, various departments of the U.S. government (especially the Department of Energy and the U.S. Nuclear Regulatory Commission), the nuclear industry, and the financial community. Given the urgency of the need to respond to climate change, it is important to seek the prompt resolution of issues associated with commercialization of low-carbon technologies.

REFERENCES

Aborn, J., E. Baik, S. Benson, A.T. Bouma, J. Buongiorno, J.H. Lienhard, J. Parsons, and Q.J. Wei. 2021. "An Assessment of the Diablo Canyon Nuclear Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Production." Stanford University Precourt Institute of Energy. https://energy.stanford.edu/publications/assessment-diablo-canyon-nuclear-plant-zero-carbon-electricity-desalination-and.

Anderson, J., and W. Freebairn. 2021. "FEATURE: U.S. Nuclear Power Plant Retirement Risk Fluctuates with Policy, Power Prices." May 3. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/050321-feature-us-nuclear-power-plant-retirement-risk-fluctuates-with-policy-power-prices.

Birch, S. 2020. "Oklo Pilots Streamlined Application Process for Micro Reactor Design." Reuters Events—Nuclear, January 9, 2020. https://www.reutersevents.com/nuclear/oklo-pilots-streamlined-application-process-micro-reactor-design.

Clearpath. 2022. "Hawkeye State Headwinds: A Case Study of Local Opposition and Siting Challenges for Large Scale Wind Development in Iowa." https://static.clearpath.org/2022/07/hawkeye-headwinds-report-large.pdf.

DOE-LPO (Department of Energy Loan Programs Office). n.d. "Advanced Nuclear Energy Projects Loan Guarantees." Energy.gov, https://www.energy.gov/lpo/advanced-nuclear-energy-projects-loan-guarantees.

DOE-NE (Office of Nuclear Energy). n.d. "Advanced Reactor Demonstration Program." Energy.gov, https://www.energy.gov/ne/advanced-reactor-demonstration-program.

EIA (U.S. Energy Information Administration). 2021. "Electricity in the U.S." eia.gov. March 18. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php.

Energy Futures Initiative. 2017. The U.S. Nuclear Energy Enterprise: A Key National Security Enabler. https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2022/02/The-U.S.-Nuclear-Energy-Enterprise_A-Key-National-Security-Enabler_Report_August-2017.pdf.

GAIN. n.d. "GAIN (Gateway for Accelerated Innovation in Nuclear)." https://gain.inl.gov/SitePages/What%20is%20GAIN.aspx.

IEA (International Energy Agency). 2021. *The Role of Critical Minerals in Clean Energy Transitions*. IEA, Paris. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

IEA. 2022. Nuclear Power and Secure Energy Transitions. https://iea.blob.core.windows.net/assets/016228e1-42bd-4ca7-bad9-a227c4a40b04/NuclearPowerandSecureEnergyTransitions.pdf.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2021. *The Future of Electric Power in the United States*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25968.

NASEM. 2022. *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.

National Research Council. 2009. *America's Energy Future: Technology and Transformation*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12091.

NRC (U.S. Nuclear Regulatory Commission). 2022. "NRC Denies Oklo Combined License Application for Lack of Information; Company May Reapply in the Future," January 6. https://www.nrc.gov/reading-rm/doc-collections/news/2022/22-002.pdf.

NRIC. n.d. "NRIC (National Reactor Innovation Center)." https://nric.inl.gov.

NSUF. n.d. "NSUF (Nuclear Science User Facilities)." https://nsuf.inl.gov.

Nuclear Energy Agency. 2022. "Meeting Climate Change Targets: The Role of Nuclear Energy." https://www.oecd-nea.org/jcms/pl_69396/meeting-climate-change-targets-the-role-of-nuclear-energy.

NuScale Power. 2022. "The Carbon Free Power Project." https://www.nuscalepower.com/projects/carbon-free-power-project.

Oklo. 2022. "What's Next." Medium, January 11. https://okloinc.medium.com/whats-next-566bb49b74dc.

Ong, S., C. Campbell, P. Denholm, R. Margolis, and G. Heath. 2013. "Land-Use Requirements for Solar Power Plants in the United States." NREL/TP-6A20-56290, 1086349. Golden, CO: National Renewable Energy Laboratory. https://doi.org/10.2172/1086349.

Save Clean Energy. 2022. "Letter to Gavin Newsom RE Diablo Canyon." https://drive.google.com/file/d/1wpKHHQD9IVHDQOQPLMFYIHPt5x0kLm0_/view?usp=embed_facebook.

Shirvan, K. 2022. "Overnight Capital Cost of the Next AP1000." https://web.mit.edu/kshirvan/www/research/ANP193%20TR%20CANES.pdf.

TerraPower. 2021. "Natrium™ Reactor and Integrated Energy Storage." TerraPower: A Nuclear Innovation Company. https://www.terrapower.com/our-work/natriumpower.

Tony, M. 2022. "West Virginia Bill Eases Nuclear Power Restrictions." GovTech. February 9. https://www.govtech.com/policy/west-virginia-bill-eases-nuclear-power-restrictions.U.S.

UAMPS (Utah Associated Municipal Power System). 2020. "Carbon Free Power Project." UAMPS Smart Energy. https://www.uamps.com/Carbon-Free.

United Nations Economic Commission for Europe. 2021. "Life Cycle Assessment of Electricity Generation Options." Geneva: United Nations. https://unece.org/sites/default/files/2021-10/LCA-2.pdf.

WNA (World Nuclear Association). 2022a. "Nuclear Power in the World Today." World Nuclear Association. February. https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx.

WNA. 2022b. "Plans for New Reactors Worldwide." World Nuclear Association. February. https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx.

WNN (World Nuclear News). 2021. "TerraPower Circles 2023 for Natrium Construction Permit." World Nuclear News, June 18. https://world-nuclear-news.org/Articles/TerraPower-eyes-Natrium-construction-permit-in-202.

Yurman, Dan. 2021. "TerraPower Selects Kemmerer WY for Natrium Reactor." *NeutronBytes* (blog), November 18. https://neutronbytes.com/2021/11/18/terrapower-selects-kemmerer-wy-for-natrium-reactor.

2

Advanced Reactor Technologies

Advanced nuclear reactor technologies hold the promise for safer, more efficient, and more nimble designs than currently deployed nuclear technologies. Advanced reactor systems include small modular light water reactors (LWRs) as well as reactors that use non-water coolants and higher ^{235}U enrichments (WNA 2020). Many of these systems were considered in the past, and some prototypes were built and operated. However, advances in materials, fuels, and other enabling technologies have been incorporated into these advanced reactor systems that may improve safety or reduce cost. A common characteristic of most of these reactor technologies is the smaller reactor system size compared to current large LWRs; these systems could be as large as a few hundred MWe or as small as a few MWe (so-called microreactors).[1] With the smaller size, the intent is to manufacture a major portion of plant components (or entire systems) in a controlled factory setting, which could reduce costs, including on-site construction costs. Multiples of these reactor system modules could be located on the same site to obtain the power capacity required. Installation of these reactor modules could be staggered over time to complement an owner-operator's integrated resource plan or financing. This chapter examines the spectrum of advanced reactor technologies that are currently under development, including their design and safety attributes, fuels and materials development, and technology readiness and gaps.

DESIGN CHARACTERISTICS

As shown in Table 2-1, advanced reactor technologies can be characterized by their neutron spectrum, the nuclear fuel, and the coolant used for heat transport (Reitsma et al. 2020). The neutron spectrum refers to the kinetic energy of the neutrons in the reactor that causes the sustained fission chain reaction. Fission neutrons are born at high kinetic energies near 1 MeV (i.e., fast) and can be slowed down by collisions with a moderator to kinetic energies near ambient temperature, corresponding to ~0.025 eV (i.e., thermal). Fast reactors do not require a moderator to slow down the neutrons; thus, the fission reactions occur only at high neutron energies. Thermal reactors require a moderator (e.g., water or graphite) to slow down the neutrons, and most of the fissions occur at low energy. The nuclear fuel contains the fissionable material (e.g., uranium) that interacts with the neutrons. The coolant that circulates through the reactor core transfers heat produced in the reactor to the electrical generator or other systems that directly utilize the heat. Many key reactor features (e.g., operating temperature, pressure, materials) are designed to ensure compatibility with the fuel and the coolant. For example, most existing nuclear plants are thermal fission reactors that use uranium in oxide form clad with zirconium alloys and cooled with ordinary water ("light water") with structural members composed of steel alloys.

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[1] Note that for electricity production, reactor size is quoted in MWe, but in some future applications, the thermal heat from the reactor (MWth) is directly used as an energy product. The thermal efficiency is the ratio of MWe to MWth, typically 33–50 percent.

TABLE 2-1 Classification of Advanced Nuclear Systems by Neutron Spectrum, Fuel, and Coolant

Reactor Technology	Neutron Spectrum	Nuclear Fuel[a]	Coolant	Example Reactor Designs
Small modular light water reactor	Thermal	UO_2	Water	NuScale, GEH-BWRX, Holtec
Liquid metal fast reactor	Fast	Uranium-metal[b]	Sodium	GE–Prism, TerraPower-GEH–Natrium
High-temperature gas reactor	Thermal	TRISO UCO[b]	Helium	X-Energy–Xe-100
Gas fast reactor	Fast	UO_2, UC[b]	Helium	GA–EM2, FMR
Fluoride-salt cooled reactor	Thermal	TRISO UCO[b]	Flibe[c]	Kairos–Hermes
Molten-salt-fuel-cooled reactor	Thermal or fast	UF or UCl salt[b]	Same as fuel	Terrestrial Energy–IMSR, Moltex, TerraPower
Heat-pipe-cooled reactor	Thermal or fast	TRISO or UO_2[b]	Heat pipe	Westinghouse–eVinci, Oklo–Aurora,[d] BWXT–BANR

[a] UO_2 = uranium dioxide; TRISO UCO = tri-structural isotropic fuel of uranium oxycarbide; UC = uranium carbide; UF = uranium fluoride salt; UCl = uranium chloride salt.
[b] These advanced non-LWR designs use high-assay low-enriched uranium (HALEU, <20 percent ^{235}U).
[c] Flibe = lithium fluoride-beryllium fluoride molten salt.
[d] Oklo's design may have changed.
SOURCE: Committee generated using F. Reitsma, M.H. Subki, J.C. Luque-Gutierrez, et al., 2020, *Advances in Small Modular Reactor Technology Developments: A Supplement to IAEA Advanced Reactors Information System (ARIS)*, Austria: International Atomic Energy Agency, https://aris.iaea.org/Publications/SMR_Book_2020.pdf.

The different design characteristics of these advanced reactor systems are summarized in Table 2-2, and more detailed descriptions can be found in Appendix A. The reactor designs listed as examples are from U.S. developers and include most of the non-LWR design concepts.[2] Except for the small modular LWRs, all of these advanced reactor systems are designed to have reactor outlet temperatures higher than those of conventional LWRs, resulting in 10–50 percent higher overall thermal efficiency—that is, thermal efficiencies of 35–50 percent for advanced reactors compared to 31–33 percent for LWRs. Assuming that these advanced designs can achieve comparable capacity factors to current LWRs,[3] this design choice is a factor that helps to reduce the cost per unit of energy produced relative to current LWRs. It also reduces the amount of energy that is rejected to the environment and the associated cooling water usage. Water use could be eliminated entirely if dry cooling technology were used. This design choice eliminates the need to be sited close to large bodies of water and presents the possibility of siting in arid regions. However, using dry cooling technology could reduce the thermal efficiency of the plant as

[2] The supercritical water reactor is not considered a viable advanced reactor design and was not considered in this study.
[3] LWRs have achieved capacity factors more than 90 percent. Advanced reactors may have lower initial capacity factors, similar to early LWRs (~50–60 percent), in the initial operation of demonstration plants. Given operational experience and continuous improvements in operations, higher capacity factors would be expected—for example, the EBR-II test reactor achieved capacity factors of ~80 percent.

the temperature of heat rejection increases. Advanced reactor systems may require higher uranium enrichment levels than the 5 percent ^{235}U currently used in LWRs. This would enable these reactor systems to operate for longer time periods with better fuel utilization. Reactor designers are considering ^{235}U fuel enrichment levels in the range of 10–20 percent (i.e., high-assay, low-enriched uranium [HALEU] fuel), which would enable these fuel systems to achieve fuel burnups up to 2–3 times higher than the current fleet of LWRs. However, this more efficient use of the uranium fuel must be balanced against the higher costs of producing it as well as developing its attendant infrastructure, such as fuel fabrication facilities.

TABLE 2-2 Selected Technical Characteristics of Advanced Small Modular Reactor Systems

Reactor Type	Core Outlet Temperature and Pressure	Thermal Efficiency	Fuel Burnup[a]	Example Reactor Designs
Small modular light water reactor	~560–590 K ~70–140 bar	~31–33%	5–6 atom% using shorter length LWR fuel rods	NuScale, Holtec, GEH–BWRX
Liquid metal fast reactor	~750–850 K ~ Few bars	~35–40%[b]	7–10 atom% using metallic fuel with recycle; >40% once-through with fuel shuffling	GE–Prism, TerraPower-GEH–Natrium
High-temperature gas reactor	~1000–1100 K ~ 70–100 bar	~43–50%[b]	10–20 atom% using TRISO fuel	X-Energy–Xe-100,
Gas fast reactor	~1000–1100 K ~ 70–100 bar	~43–50%[b]	14 atom% using UC or UO_2 fuel in SiC clad	GA–EM2, FMR
Fluoride-salt-cooled reactor	~900–950 K ~Few bars	~42%[b]	Similar to HTGR using TRISO fuel with similar burnup	Kairos–Hermes
Molten-salt-fuel-cooled reactor	~900–950 K ~Few bars	~40–42%	High fissile burnup with dissolved fuel in coolant; burnup limits by reactivity issues	Terrestrial Energy–IMSR, Moltex, TerraPower
Heat-pipe-cooled reactor	~750–800 K Low pressures	~30%	5–20 atom% using TRISO fuel	Westinghouse–eVinci, Oklo–Aurora,[c] BWXT–BANR

[a] Atom% designates the percentage of fissile and fertile atoms that undergoes fission in the fuel. Note that 1 atom% is approximately equivalent to 9.5 GW-days/metric Ton U.

[b] Thermal efficiency depends on outlet temperature.

[c] Oklo's design may have changed

SOURCES: Committee generated using F. Reitsma, M.H. Subki, J.C. Luque-Gutierrez, et al., 2020, *Advances in Small Modular Reactor Technology Developments: A Supplement to IAEA Advanced Reactors Information System (ARIS)*, Austria: International Atomic Energy Agency, https://aris.iaea.org/Publications/SMR_Book_2020.pdf; D. Petti, R. Hill, J. Gehin, et al., 2016, "Advanced Demonstration and Test Reactor Options Study," INL/Ext-16-37867; D. Petti, R. Hill, J. Gehin, et al. 2017, "A Summary of the Department of Energy's Advanced Demonstration and Test Reaction Options Study," *Nuclear Technology* 199:111–128, https://doi.org/10.1080/00295450.2017.1336029; Nuclear Energy Agency—Organisation for Economic Co-operation and Development, 2021, "Advanced Nuclear Reactor Systems and Future Energy Market Needs," NEA No. 7566, *Nuclear Technology Development and Economics*, Paris: Nuclear Energy Agency, https://www.oecd-nea.org/upload/docs/application/pdf/2021-12/nea_7566_arfem.pdf.

SAFETY CHARACTERISTICS

The safety of a nuclear reactor system depends on a set of safety functions that must be satisfied to control the reactor and ensure its safety given the occurrence of an accident. The safety functions include

- Control of reactor reactivity[4] during startup, operation, and shutdown.
- Control of heat removal to an ultimate heat sink.
- Containment of radiological materials.

These safety functions should guarantee reactor control under normal operation, shutdown when called on, and removal of residual heat from the reactor for long-term cooling once the reactor is shut down. A full range of possible accidents from internal events must be analyzed to demonstrate that these safety functions are fulfilled. These accidents would include unanticipated power increases, loss of coolant inventory from the reactor core, loss of heat rejection to the ultimate heat sink, as well as internally caused fires or floods. External hazards must also be considered and accommodated. These external hazards include natural events such as earthquakes, tornadoes, external fires, or floods as well as human-made hazards owing to unintentional or intentional acts outside the plant. The objective of these safety analyses is to show via testing and modeling that all the safety functions are satisfied and that the design prevents the release of any radioactive materials into the environment (or limits any releases to acceptable levels).

Nuclear reactors must be designed based on safety criteria that result in safety features and systems that can reliably accomplish these safety functions. Specific design features and operation and maintenance of support systems (electric power, cooling, pressurized air, etc.) may be required. Reactor designs must also provide, where appropriate, physical separation, independence, diversity, and redundancy in the safety systems to reduce the likelihood of common-cause or single-point failures that could lead to failure in executing the required function. Last, designs must use sufficient engineering design margins to cover the possibility that challenges to safety functions could arise from an incomplete understanding of reactor system behavior. The "Defense-in-Depth" concept, meaning that the design includes independent systems to ensure a safety function is satisfied, is an integral part of any reactor design. These design principles are intended to ensure that all safety functions are successfully satisfied, and that the overall reactor system is safe and provides adequate protection to the public and the environment.

In currently operating LWRs, key safety functions are accomplished by a diverse and redundant combination of backup systems (e.g., auxiliary diesel generators for AC-powered electrical systems, additional independent water pumping systems), alternative sources of water, and prescribed operator actions. These systems reduce the likelihood of safety system failure and mitigate the consequences if a failure were to occur. Specific design criteria are established so that system conditions that could drive possible radiological releases are mitigated and controlled for a range of postulated accidents that form the design basis for the specific engineering system: these are called design-basis accidents. This approach has proven successful, and LWRs operate with a high degree of reliability and safety.

Advanced reactor systems would rely more on inherent and passive[5] design features than current LWRs. For example, the NuScale small modular LWR design virtually eliminates the need for active

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[4] Reactivity is the term used to express the departure of a reactor system from criticality, which defines a state in which the rate of neutron production from fission equals the rate of neutron absorption. A negative reactivity addition indicates a move toward a power decrease. A positive reactivity indicates a move toward a power increase.

[5] The International Atomic Energy Agency (IAEA) defines active, passive, and inherent safety features as follows: "Active safety features 'rely on external electrical or mechanical power, signals, or forces to complete a safety function.' Passive safety features 'only require natural forces (gravity or gas pressure), properties of materials, or internally stored energy (e.g., mechanical spring forces) to complete a safety function.' Inherent features 'rely on

systems to accomplish safety functions, relying instead on a combination of passive systems (e.g., safety relief valves driven by gas pressure or spring forces, gravity-driven water flow) and the inherent features of its design geometry and materials (e.g., large water inventory with high thermal capacity). Non-LWR advanced reactor systems have taken a similar approach, accomplishing key safety functions in the system design with a much greater emphasis on inherent and passive features, as noted in Table 2-3. These small modular reactors (SMRs) can also employ integral designs that can incorporate all key components in the primary vessel, thereby reducing the risk from pipe breaks, because the primary coolant remains in the vessel. This configuration is significantly larger than a traditional loop configuration and increases the thermal inertia of the system.

The different fuels, coolants, and moderators (in thermal reactors) used in advanced reactor designs affect the inherent safety of the system through the basic material properties, neutronics designs, and chemical characteristics of system components. Non-LWR advanced reactor designs have the potential to improve safety by a combination of the following safety attributes that minimize the challenges to their systems for a wide range of transients and accidents (see Table 2-3):

- Negative reactivity coefficient for helium-cooled thermal reactor systems and sodium-cooled fast reactor systems causes a reactor power decrease for a reactor temperature increase.
- Single-phase coolants during normal operation with large margins to boiling for liquid coolants keep the reactor core cooling effective over a wide temperature range.
- High thermal conductivity and high heat capacity for liquid coolants (e.g., sodium and molten salts) removes heat from the reactor more effectively and reduces the rate of temperature increase.
- High heat capacity for the graphite moderator in gas-cooled and molten-salt thermal systems reduces the rate of temperature increase in the reactor core.
- Low chemical reaction rates of single-phase coolants like helium and molten salts reduce the potential for materials degradation.
- Fuel design with robust tristructural isotropic (TRISO) fuel kernels used in gas-cooled and some molten-salt thermal systems reduces fuel failure rates at high temperatures.
- Strong fission product retention in sodium, molten salts, and graphite moderator reduces the amount of radioactive material release from the reactor system.

fundamental properties (materials or design choices that cannot be changed by internal or external conditions) to complete a safety function.' " (IAEA 1991).

TABLE 2-3 Safety Characteristics of Advanced Reactors

Reactor Type	Passive and Inherent Safety Characteristics	Exampl[e] Reactor
Small modular LWR (SMR) (water coolant)	• Designs use natural forces (gas pressure, water gravity head, stored energy) to perform safety functions, allowing for long-term decay heat removal to the ultimate heat sink.	NuScale BWRX,
Liquid metal cooled fast reactor (SFR) (sodium)	• Design achieves reactor shutdown by negative power reactivity feedback for accidents with a failure to insert control rods to shut down the reactor (SCRAM). • Low-pressure conditions with a large pool inventory eliminate loss of coolant accidents. • Long-term decay heat removal to heat sink using natural forces of density change and gravity head.	GE–Pris TerraPo Natrium
High-temperature gas reactor (HTGR) (helium coolant)	• Design achieves reactor shutdown by negative temperature reactivity feedback for accidents with a failure to SCRAM. • Temperature increases owing to loss of coolant accidents minimized by low power density and high thermal conductivity and heat capacity of reactor core materials. • Long-term decay heat removal to heat sink using natural forces of density change and gravity head.	X-Energ
Gas fast reactor (GFR) (helium coolant)	• Design features (e.g., low power density, fuel, clad and reflector materials) can attain a degree of passive safety.[a]	GA–EM
Fluoride salt-cooled (FHR) (Flibe salt coolant)	• Design incorporates HTGR safety features with large heat capacity and natural circulation aspects of molten salt. • Low-pressure conditions with a large pool inventory eliminate loss of coolant accidents. • Long-term decay heat removal to heat sink using natural forces of density change and gravity head.[a]	Kairos–
Molten-salt-fuel-cooled (MSR) (U-F or U-Cl salt coolant/ fuel)	• Design achieves reactor shutdown by gravity drain tanks with a fuel melt plug actuation upon a failure to SCRAM. • Minimal heat content in off-gas system with fission products.[a]	Terrestri IMSR, M TerraPo
Heat-pipe cooled (low-pressure liquid metal)	• Heat pipes achieve cooling by natural forces in the design. • Temperature increases owing to heat pipe failures minimized by low power density and high thermal inertia of materials. • Long-term decay heat removal to heat sink provided by heat conduction from reactor system to surroundings.[a]	Westing eVinci, BWXT–

[a] Demonstration is required by integral testing of this safety feature.

SOURCES: Committee generated using D. Petti, R. Hill, J. Gehin, et al., 2016, "Advanced Demonstration and Test Reactor Options Study," INL/Ext-16-37867 and D. Petti, R. Hill, J. Gehin, et al., 2017, "A Summary of the Department of Energy's Advanced Demonstration and Test Reaction Options Study," *Nuclear Technology* 199:111–128, https://doi.org/10.1080/00295450.2017.1336029.

The sodium-cooled fast reactor and the high-temperature gas-cooled reactor have well-developed designs and have confirmed many of their safety characteristics through actual integral testing in prototype reactor plants (Planchon et al. 1987; Kunitomi et al. 1990). In addition, these advanced reactor designs have incorporated passive safety systems that use natural circulation for decay heat removal and long-term core cooling. The overall plant design allows for fewer auxiliary components or systems that may also reduce reactor system costs. These designs have the potential to accomplish safety functions without the need for AC power and can allow for extended coping times during transients and accidents. For example, in a loss of coolant flow accident that may occur in a high-temperature gas-cooled reactor, the reactor temperature increase is much slower, rising over several hours, compared to seconds for current LWRs. Such design attributes also have the potential to significantly reduce the accident source term and may allow for more flexible siting of these reactor systems near population centers.

Regardless of design specifics, the qualitative safety characteristics and design attributes are similar across many non-LWR advanced reactor types, including less mature concepts (e.g., molten-salt reactor). Nevertheless, there is a lack of operational experience with these designs, and trained operators for these new advanced reactor designs will have to be developed. Demonstration of these safety functions still needs to be validated with appropriate operating experience and collection of integral test data at appropriate scales to demonstrate capabilities and to confirm the satisfaction of safety requirements (see Table 2-3).

To improve safety and operational efficiency, advanced reactor designs are likely to incorporate extensive use of digital controls, advanced sensors, and data science capabilities such as artificial intelligence (AI). In current LWRs, the wealth of data involving plant and component performance is now being used to enable enhancements in automation, autonomous risk detection, predictive maintenance, and asset performance management (Al Rashdan et al. 2018; Gohel et al. 2020). For advanced reactors, automation and autonomous risk detection may also have the potential to improve safety by diminishing the demands on operators and reducing the potential for human error. Safety and reliability can be enhanced by continuous monitoring of component status and performing maintenance or replacing components as needed rather than on a time-based schedule. This can avoid unnecessary maintenance that can cause failures. Sophisticated data collection combined with inherent self-regulating physics in microreactors has been suggested as a motivation to consider autonomous control for those designs. However, as more reliance is placed on digital systems and AI, strong cybersecurity principles and clear guidance on when and how to trust AI will become increasingly important. These advanced reactor designs will need to meet the cybersecurity consensus codes and standards that are now being established by regulatory agencies. For example, the U.S. Nuclear Regulatory Commission (NRC, 10 CFR 73.54) requires that nuclear facilities provide high assurance that digital computer and communication systems and networks are adequately protected against cyber-attack. The requirements for cybersecurity are discussed in Chapter 9.

Despite these positive design characteristics, safety challenges remain for advanced reactors, particularly to ensure reliable operation and to cope with postulated accidents. These issues will need to be addressed for each specific design given their unique design features. Gas-cooled reactors must control and limit the level of air or water ingress into the reactor system to minimize the amount of graphite oxidation, thereby reducing radioactive releases from the reactor to the surrounding building and the environment. Molten-salt-cooled reactors will require careful chemistry and temperature controls to mitigate material corrosion and salt freezing in piping during operation. Sodium fast reactors must maintain an inert atmosphere and water-free conditions to preclude chemical reactions from sodium leaks. Such events have plagued some past versions of this design and have resulted in extended plant shutdowns. Beyond the typical design-basis accidents that need to be considered for reactor systems (e.g., loss of flow, loss of coolant, power transients), sodium fast reactors must consider the possibility of air or water ingress and the resultant effects of sodium fires, and the safety systems needed to mitigate these effects. Such unique design features for any of the advanced reactors must be considered and analyzed to ensure safe operation.

Therefore, while these advanced reactor designs have the potential to demonstrate that required safety functions can be accomplished, the designs will need to demonstrate that they can meet the standards established by the government regulatory body (e.g., NRC in the United States) by integral testing as well as appropriate supporting safety analyses. The regulatory standards that are being developed specifically for advanced reactors (e.g., siting near population centers and required emergency planning zones) are discussed in more detail in Chapter 7.

Finding 2-1: Many advanced reactor designs employ a combination of fuel, coolant, and moderator that result in a set of core components with potentially inherent favorable safety characteristics (e.g., physical stability, high heat capacity, negative reactivity feedbacks). The designs also include engineered passive safety systems that incorporate no active components (e.g., pumps, motor-activated valves) and could require no emergency AC power and fewer external operator actions. These inherent and engineered design attributes, if actualized, have the potential to make fulfilling key safety functions (i.e., reactivity control, heat removal, radioactivity containment) simpler, more reliable, more cost effective, and more tolerant of human errors. Employing sophisticated sensing and data collection could further improve safety by increasing component and systems reliability.

Finding 2-2: Reactor designers and owners must demonstrate that key safety functions (i.e., reactivity control, heat removal, radioactivity containment) are satisfied during normal operation, transients, and the full range of possible accidents. (The list of possible accidents considered for new and advanced reactor designs could be different from those considered for current light water reactors [LWRs].) This will require collection of integral test data at appropriate scales and operating experience, supplemented by supporting analyses. The safety risks associated with small and advanced reactors differ from those for conventional LWRs and require new testing facilities and demonstration facilities.

Recommendation 2-1: The Department of Energy should evaluate the need for common experimental facilities that would help provide the required testing to support licensing and long-term operations across multiple reactor concepts within a reactor class (e.g., gas-cooled or molten-salt-cooled concepts).

FUEL AND MATERIALS INNOVATION, DEVELOPMENT, AND MANUFACTURING

The fuel and materials selection process has a major impact on the feasibility of advanced reactor concepts. Many of the advanced reactor concepts would utilize new fuel geometries and/or higher fissile isotope enrichment levels compared to conventional LWR fuel (i.e., solid uranium-oxide pellets with ^{235}U enrichment less than or equal to 5 percent). Therefore, new fuel supply chain systems need to be commercially established and qualified for the advanced reactors to use them to achieve widespread deployment. Issues associated with developing higher enrichment fuels are discussed in a companion National Academies study (NASEM 2022). In general, development of HALEU supply chain infrastructure is a crosscutting challenge for the realization of many of the proposed advanced reactor concepts. Some initial federal funding to establish commercial-scale HALEU feedstock capability has been recently appropriated ($700 million in the Inflation Reduction Act [IRA] of 2022, P.L. 117-169). Furthermore, some of the advanced reactor concepts use different fuel forms such as TRISO particles embedded in a variety of fuel matrix structures (Tables 2-1 and 2-2), which will also require maturation from laboratory-scale to commercial-scale production.

Additionally, because advanced reactors generally operate at higher temperatures and in environments that are different (more challenging) than the existing commercial reactors, the technology gaps for nearly every advanced reactor concept include the need to develop and qualify high-performance materials with improved high-temperature strength and resistance to corrosion and irradiation effects (see Table 2-4). Materials with greater high-temperature strength or high-temperature corrosion resistance would allow for thinner components, improved safety margins, and improved thermodynamic efficiencies and economics for high-temperature reactors (Busby 2009; Zinkle et al. 2016). It should be noted that advanced reactor concepts do not require advanced materials for all reactor components; in many cases, conventional materials would be acceptable. However, some key components in demanding operational environments would benefit from new high-performance materials. One example is advanced cladding materials for sodium-cooled fast reactors that would simultaneously enable high fuel burnups (>15 percent) and thermodynamically favorable high reactor outlet temperatures (>850 K).

Only six alloys are currently code qualified for ASME Boiler and Pressure Vessel Section III, Division 5 (High Temperature Reactors). All of these code-qualified Fe- and Ni-base alloys were developed 35 to 100 years ago and, in general, have properties significantly inferior to more recent commercial alloys. In contrast, dozens of higher-performance alloys have been commercialized (and code-qualified for non-nuclear applications) in the past 20 years for demanding fossil energy and aerospace applications (Viswanathan et al. 2013). If the engineering designs of advanced reactors are limited to these six code-qualified high-temperature reactor materials, significant performance limitations will result (Zinkle et al. 2016; Pathania 2012). Additionally, ASME Section III, Division 5 code qualification does not address any degradation effects associated with corrosion, mass transfer phenomena, or radiation effects in the operating environment. It is generally acknowledged that materials corrosion and radiation effects can impose greater operational restrictions on reactor designs than the “design allowable” restrictions associated with tensile properties, thermal creep, or fatigue/ratcheting effects that are addressed by the ASME code. This suggests there may be value in a coordinated public–private research and development activity for advanced (high performance commercialized) materials that encompasses ASME (or equivalent) code qualification along with reactor-relevant irradiation/corrosion environmental test conditions, as discussed later in this section.

There are at least four potential options to mitigate operational performance gaps associated with using the current limited set of ASME code-qualified materials for advanced reactors: (1) introduce design innovations to reduce the required materials properties, (2) use reduced design margins, (3) introduce advanced high-performance materials and/or advanced manufacturing concepts, or (4) derate the reactor concept operating parameters (temperature, operating lifetime, etc.). Considering the significant improvements in materials properties—such as high-temperature creep strength, high fracture toughness, enhanced corrosion resistance, and improved radiation resistance—that can be attained in specific application-selected materials, option (3) offers considerable promise. For example, recently developed ferritic alloys simultaneously exhibit up to a factor of two increased thermal creep strength and greater than a factor of two improved dose before the onset of deleterious void swelling (Zinkle et al. 2016, 2017). Use of such materials for cladding and fuel assembly ducts for sodium-cooled fast reactors could enable desired deep burnup levels and high operational temperatures to be achieved that could dramatically improve fuel utilization and economics. Similar benefits associated with advanced materials could be realized for high-temperature gas-cooled reactors and molten-salt reactors.

International collaboration (via the Generation IV International Forum or other avenues) might be beneficial for assembling the broad range of experimental data needed to develop an ASME Section III, Division 5 code case (or equivalent alternatives) for one or more high-performance commercial alloys. For example, the Electric Power Research Institute (EPRI) released a high-level roadmap to enable coordination of materials development and validation programs to support the near-term deployment of non-LWR designs (EPRI 2021a). Regulatory acceptance and economic considerations for prospective new materials typically require development of an ASME (or equivalent) code case and understanding of degradation processes associated with corrosion, creep fatigue, and neutron irradiation damage. These historically require a decade or longer to complete, challenging the introduction of higher performance materials. To reduce the time for new materials to gain regulatory acceptance, a staged approach for qualifying advanced materials could be envisioned for introducing new materials.

In the first phase, limited duration testing (up to several years) could be performed to develop an ASME Section III, Division 5 code case for limited lifetimes that might be relevant for a prototype or demonstration reactor system. Longer duration testing could be performed in parallel that could subsequently extend the code qualification to longer lifetimes and higher temperatures. This approach also provides for parallel evaluation of critical degradation mechanisms (corrosion, irradiation, etc.) in advanced reactor environments. The stakeholders in such a staged approach could involve public–private partnership (e.g., DOE-NE and EPRI). The general concept of a staged approach for materials qualification (extending beyond traditional ASME code qualification) has been used several times in the past; a well-known safety-relevant example is the periodic testing of LWR reactor pressure vessel coupons during every fuel replacement outage to ensure safe operation of the pressure vessel.

Advanced manufacturing concepts such as additive manufacturing, powder metallurgy–hot isostatic pressing (PM-HIP), and advanced welding and cladding methods also offer multiple potential benefits. For example, design and fabrication of advanced fuels incorporating TRISO fuel particles based on uranium nitride (UN) kernels have been demonstrated and provide a factor of three higher fissile atom density compared to traditional uranium oxy-carbide (UCO)-based TRISO fuel systems (Terrani et al. 2021). Of even greater potential benefit is the possibility of utilizing in situ diagnostic monitoring during the additive manufacturing build that, combined with advanced data analytics and machine learning methods, could lead to direct quality certification of as-built components without resorting to historical post-build non-destructive or destructive analysis techniques. In addition, design and fabrication of improved high-performance reactor core configurations can be achieved by adapting multi-physics artificial intelligence (AI) techniques to design novel core geometries that can only be constructed using advanced additive manufacturing methods (Sobes et al. 2021). These design innovations enabled by advanced manufacturing have the potential to simultaneously improve safety, reliability, and economics. To take full advantage of these and other benefits of additive manufacturing, the nuclear industry (in concert with federally funded research programs) must address key obstacles, including lack of codes and standards and processing variables. Advanced manufacturing methods such as PM-HIP also provide the advantage of improved material homogeneity, reducing variability and enhancing mechanical performance at elevated temperatures while providing a domestic supply chain for major components. Advanced welding technologies like electron beam welding have the potential to significantly reduce fabrication lead times, improve quality, and avoid embrittlement of welds (EPRI 2021b). Demonstrating these technologies is critical to accelerating their application in new reactors (EPRI 2021c).

Another aspect requiring materials innovation and development for advanced reactors is the ability to maintain reactor systems from a cost and reliability perspective during operation. Many systems will expose components to high temperatures, corrosive environments, and high radiation fluxes. Without thoughtful design and materials selection, some components may need to be replaced frequently, and maintenance may be difficult to execute, either of which could add to cost, complexity, and reactor downtime. To prove survivability of components, many designers are taking new, more agile approaches than those of the past. Some companies are doing rapid testing to gain key data quickly (Kairos Power 2021). Another approach is cyber-physical systems, where simulation and physical components are used together to acquire as much real feedback as possible. In both cases, the goal is to shorten the work and time needed to demonstrate how to conduct proper maintenance and ensure that components will survive to their expected life span in the reactor system environment. It is still unclear if these new and agile approaches will result in systems that sufficiently reduce costs and maintenance.

> Finding 2-3: For all the non-light water reactors that require higher ^{235}U enrichment beyond current established levels, a new fuel supply chain system must be qualified and commercially developed. Without this fuel supply chain, widespread commercial deployment of these reactor concepts cannot be achieved. This high-assay low-enriched uranium, while one of many new supply chains that need to be established to support advanced reactors, is critical across many of the advanced concepts.

> Finding 2-4: Advanced reactor concepts, while innovative in some aspects of their design, are generally based on relatively conventional fuels, materials, and manufacturing methods. Such conventional moderate-performance materials (e.g., currently code-qualified structural steels) are suitable for many non-demanding advanced reactor components, such as primary system piping. However, notable improvements in performance and economics could be achieved by more widespread use of better-performing materials for advanced fuels, high-performance fuel cladding materials, and advanced manufacturing (e.g., additive manufacturing). While many of

the current concepts plan to move to commercial reactor demonstration with existing materials, optimization of future generations for further improvements in safety, reliability, and economics will require technology advancements.

Recommendation 2-2: The Department of Energy (DOE) should initiate a research program that sets aggressive goals for improving fuels and materials performance. This could take the form of a strategic partnership for research and development involving DOE's Office of Nuclear Energy and Office of Science, the U.S. Nuclear Regulatory Commission, the Electric Power Research Institute, the nuclear industry, national laboratories, and universities. The program should incentivize the use of modern materials science, including access to modern test reactors, to decrease the time to deployment of materials with improved performance and to accelerate the qualification (ASME Section III, Division 5 or equivalent) and understanding of life-limiting degradation processes of a limited number of high-performance structural materials—for example, reactor core materials and cladding.

TECHNICAL READINESS AND TECHNOLOGY GAPS

Several technological factors can affect the ability to demonstrate and then commercialize an advanced reactor system, including the readiness of the reactor technology to be used; the development activities needed to resolve technology gaps so that a demonstration plant can be designed, licensed, and operated; and the feasibility of full-scale demonstration to confirm that performance and operability meet requirements.[1] This section reviews the maturity of different advanced reactor systems, assessing their technical readiness and the technology gaps requiring further development. Table 2-4 summarizes key technical issues that can affect the ability to demonstrate each reactor concept.

DOE has developed a Technology Readiness Assessment Guide to assist the agency in determining the readiness of technologies under development (DOE 2009). In addition, several organizations around the world have examined the technology readiness of advanced nuclear reactor technologies, and each has applied its own specific technology readiness scales in its evaluation (GIF 2014; Gougar et al. 2015; Sowder 2015; Petti et al. 2016). These ratings of technology readiness for demonstration were based on three primary criteria: (1) the extent that further technology development is needed to resolve technical, design, and licensing issues (for fuels, cladding, coolants, or moderators); (2) prior successful operating experience with the reactor system (or similar systems); and (3) the maturity level of the existing safety demonstration of the reactor system or its key subsystems. Based on these criteria, the advanced reactor technologies have been rated on their technology readiness as follows:

- Lowest maturity: gas fast reactor (GFR), molten-salt reactor (MSR-fast), MSR (salt other than Flibe).
- Low-medium maturity: large sodium fast reactor (SFR), fluoride salt reactor (FHR), MSR (with Flibe), high-temperature gas-cooled reactor (HTGR) (>1,100 K outlet temperature), microreactors.
- Medium-high maturity: light water small modular reactors, small SFRs, and modular HTGRs (<1,100 K outlet temperature).

In the past, LWR systems have gone through a series of development steps prior to commercialization (Petti et al. 2017):

[1] Additional, non-technical factors, such as the level of investment by government and private entities in technology development and the consistent bipartisan support of a comprehensive path forward, can also affect the ability to demonstrate and commercialize an advanced reactor system, but are not discussed in detail in this chapter.

- Research and development to prove the scientific feasibility of key features associated with fuel, coolant, and reactor system components and configurations.
- Engineering demonstration at reduced scale for proof-of-concept of designs that have never been built, with a goal of demonstrating the viability of the integrated system.
- Performance demonstration to confirm effective scale-up of the system and to gain operating experience to validate the integral behavior of the system resulting in proof of performance.
- Commercial demonstration that leads to the subsequent commercial offerings.

These development stages are being used for more mature advanced reactor technologies (e.g., SFR and HTGR). Advances in fuels and enabling safety technologies have been incorporated into these advanced reactor systems to improve performance and safety. For example, SFR designs employ the operational experience of the EBR-II test reactor to develop a metal fuel for the larger SFR reactor design. The use of metal fuel coupled with the reactor core design allows the SFR to have inherent reactor shutdown capabilities for a range of postulated accidents (ANL 2020). Additionally, taking lessons from the larger Super Phenix SFR, the smaller SFR designs use modular steam generators rather than a large monolithic steam generator to improve operational reliability (albeit at the cost of additional metal needed in the construction). For the HTGR, the TRISO fuel development campaign (Petti 2016) has led to a robust fuel design that will be employed in future HTGR systems. In both these reactor designs, further safety testing will be needed in the demonstration plants to confirm their long-term cooling with passive decay heat removal capabilities. These reactor development approaches were used to overcome past difficulties experienced with these reactor design concepts.

A similar approach may also be needed for less mature technologies (e.g., FHR and MSR) if the intent is to resolve major technology gaps and complete required technology demonstration activities, gain operating experience, demonstrate effective scale-up of systems performance, and establish required supply chains. These steps are all important prerequisites to offering commercial versions of these advanced reactor technologies. Reactor vendors could also consider developing a prototype plant prior to a full demonstration plant to test their technologies without concern about economic drivers such as outages and staffing levels.

In general, the technology development gaps identified in Table 2-4 for the more mature advanced reactor technologies are related to regulatory qualification of unique systems and extension to new performance regimes—for example, develop and qualify unique reactor components, and qualify improved fuels and materials. While the level of technical readiness is substantial for mature reactor concepts, it is important that the industry not be prone to optimistic schedules and underestimate the time and the associated effort required to qualify these systems and components along with the requirements for full-scale demonstration.

TABLE 2-4 Advanced Reactor Technology Experience, Technology Readiness, and Technology Gaps[a]

Reactor Type	Technology Experience	Technology Readiness	Technology Gaps
Small modular LWR	Evolution to advanced designs from currently operating LWRs.	High technology readiness with significant similarity to operating LWRs	Development and qualification of unique plant components (e.g., single-failure-proof valves)
Liquid metal cooled fast reactor (sodium)	Several small sodium-cooled fast reactors operating worldwide.	High technology readiness for small SFR Low–medium technology readiness for higher burnup breed/burn cores for SFRs	Qualification of annular metal fuel as a transition from sodium-bonded metal fuel Qualification of advanced steel alloys for use with high fuel burnup breed/burn cores (clad and structure) Source term experiments that reduce conservatisms
High-temperature gas reactor (helium)	Several small helium-cooled high-temperature reactors operating worldwide.	Medium–high technology readiness for <1,100 K outlet temperature design Low–medium technology readiness for >1,100 K outlet temperature design	For <1,100 K outlet temperature, qualification of fuel and graphite for use in reactor demonstration plant For >1,100 K outlet temperature, qualification of materials used in heat exchanger and other components
Gas fast reactor	No reactor ever built.	Low technology readiness	Qualification of fuel, clad, and structural materials for safety and for radiation damage Demonstration of passive safety systems
Fluoride high-temperature salt-cooled reactor (FHR) with Flibe	FHR was designed; Hermes is a reduced-scale prototype and is planned for demonstration.	Low–medium technology readiness for Flibe systems	Demonstration of corrosion/control for Flibe-based salt in the presence of a neutron field Demonstration of materials to show strength, corrosion resistance, and irradiation stability in operation Demonstration of tritium mitigation and radioactivity control in primary system and off-gas systems Demonstration of passive safety systems
Molten-salt-fuel-cooled reactor (U-F molten salt coolant and fuel)	ORNL experiments were operated without power conversion systems.	Low technology readiness for thermal and fast systems	Each design is unique but has similar gaps to the FHR: e.g., corrosion control for salts, tritium migration and control, materials to be used for long-term operation or replacement materials Demonstration of passive safety systems

Heat-pipe cooled (low-pressure liquid metal)	LANL space reactor demonstrated this concept at reduced power scale.	Low–medium technology readiness for thermal and fast systems	Development of compact power conversion unit (PCU) operation and PCU integration with heat-pipe core cooling Development of autonomous control and instrumentation Demonstration of passive safety systems

[a] For all of the non-LWRs using higher enrichment fuel, there remains the need to identify a commercial fuel vendor.

SOURCES: Committee generated based on Generational IV International Forum, 2014, “Technology Roadmap Update for Generation IV Nuclear Energy Systems,” https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf; H.D. Gouger, R.A. Bari, T.K. Kim, et al., 2015, *Assessment of the Technical Maturity of Generation IV Concepts for Test of Demonstration Reactor Applications, Revision 2*, Technical Report, Idaho National Laboratory, Idaho Falls, Idaho, https://doi.org/10.2172/1236803; A. Sowder, 2015, *Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design—The Liquid Fluoride Thorium Reactor (LFTR)*, Technical Report, Electric Power Research Institute, https://www.epri.com/research/products/000000003002005460; D. Petti, R. Hill, J. Gehin, et al., 2016, *Advanced Demonstration and Test Reactor Options Study*, INL/Ext-16-37867; and D. Petti, R. Hill, J. Gehin, et al. 2017, “A Summary of the Department of Energy’s Advanced Demonstration and Test Reaction Options Study,” *Nuclear Technology* 199:111–128, https://doi.org/10.1080/00295450.2017.1336029.

In contrast, the technology development gaps for the lower maturity advanced reactor technologies are related to the viability and performance confirmation of key reactor features—for example, materials compatibility and corrosion behavior in a radiation field; demonstration of materials to show strength, corrosion resistance, and irradiation stability during operation; demonstration of tritium mitigation by control and monitoring; integral performance of passive safety systems. Examples of some specific technology gaps for these advanced reactor systems are provided in Appendix B.

> Finding 2-5: The various advanced reactor systems are at different levels of technical maturity. Each reactor design concept requires the completion of certain key technology development activities. The time and effort needed depends, in part, on the technical readiness of the concept and prior operating experience with the specific reactor technology involved. More mature concepts, such as advanced small modular light water reactors, small modular sodium fast reactors, and small modular high-temperature gas-cooled reactors, might be technically ready for demonstration by the end of this decade. Less mature reactor concepts require a range of additional development activities before demonstration can occur (such as qualification of fuel or structural materials for prototypic conditions) and would not be ready for demonstration until after 2030. The success in getting concepts ready for regulatory review, building a demonstration plant in a timely and predictable manner, and proving operational excellence with demonstration plants will determine potential broader commercial deployment.

OPERATION AND MAINTENANCE OF ADVANCED REACTORS

Operation

During the committee's information gathering, several reactor manufacturers presented on the concept of operations for the various advanced reactor designs. These discussions revealed that, while some operational aspects of the new designs are similar to those of existing commercial reactors, several significant differences will need to be addressed to ensure readiness for broader deployment.

Among those differences is the concept that if a "fleet" of reactors is operating on a site, reactor maintenance could be done in phases such that the overall installation would continue to provide power to the grid. This would be a positive operational aspect regarding grid connectivity and ability to provide continuous power, without losing generation capacity for a few weeks for refueling and maintenance as with current reactor plants. The ability to phase downtime would be applicable only in configurations where multiple reactors would be installed on a site.[26] Other operational models might envision mobile reactors that would be returned to a centralized facility for refueling and replaced on site by a new, fully fueled system to ensure continuity of power delivery. This model carries with it significant regulatory challenges for transporting a reactor system that contains spent nuclear fuel (see Chapter 7 for more information on regulatory issues with transportable reactors).

A number of key operations issues impact the safety, cost, operational readiness, and ultimate availability of new designs. These are not addressed in technical detail in this report, but each will require significant benefit/cost assessment, including potential regulatory and schedule risk.

- *Automation to reduce workforce requirements.* Market viability can be improved with a reduction of onsite personnel. The DOE Light Water Reactor Sustainability program has assessed increased use of automation, and the Advanced Research Projects Agency–Energy's (ARPA-E's) program "Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA)" has performed research into better operational options (DOE-NE n.d.; ARPA-E 2019). The ARPA-E program points to the need for digital twins to support transformation of

[26] Note that reactor designs using a pebble bed configuration do not require traditional refueling because refueling would be accomplished while the reactor is operating.

operations and maintenance. Automation also may include adjustable control and protective systems. In some cases, control regimes and setpoints are not fixed but are adaptive based on the performance regime for the system. This adaptability may enhance performance for any design but requires more complex software development and may increase risk for cyber intrusion and interference. Greater automation will also necessitate greater focus on fault tolerant controls. To the extent that reactor developers include the use of AI/machine learning-enabled sensing and controls, monitoring methods will require enhancement and understanding of—as well as regulatory oversight for—AI algorithms.

- *Remote monitoring.* Coupled with automation, enhanced remote monitoring, including remote regulatory oversight, may reduce the need for onsite personnel. Regulator acceptance of remote monitoring in lieu of regular onsite oversight visits may have market benefit but must be balanced with safety.
- *Safety and emergency response.* With enhanced automation, increased use of remote sensing, and reduced personnel will come the potential for increased dependency on local emergency response capabilities. In the event of fire, flooding, or seismic events, for example, some immediate response may be shifted from onsite personnel to first responders from the local community. This will necessitate a new training regimen to support response to off-normal events, which will require additional funding and resources.
- *Control schema for operating multiple plants from a single control room.* Some designers are considering control of multiple plants from a single, possibly remote, control room. Multi-unit operations from a single control room have been demonstrated by the U.S. Nuclear Navy, making this a viable concept. The USS *Enterprise* had eight reactors that were operated in pairs with summary performance for all eight monitored by a senior engineering supervisor in a central control room. Evaluation of communications pathways, reliability, and cybersecurity for monitoring systems will require analysis and perhaps may lead to increased risk, as noted in Chapter 9.
- *Consolidated maintenance.* Experience with the existing LWR fleet has demonstrated that there are major savings from well-tailored outage operations to include refueling and maintenance performed by single teams for multiple units. In the case of new advanced designs, this concept may be taken one step further to include the potential for returning some microreactor or mobile (e.g., floating) small modular systems to a central location for refueling and refurbishment. While this new operational paradigm may lead to cost savings, there are major uncertainties in terms of construction standards, transportation safety and security, and nonproliferation risk. The solutions to address these risks may present operational cost uncertainty and require further assessment.
- *Operation in non-electricity markets*. New reactor designs may allow for use of the reactor for non-electricity purposes, such as providing heat for hydrogen production when the nuclear output is not needed for the grid. This presents new operational considerations with potentially higher operational and market risk.
- *Security controls and limits.* As with the need to enhance security and cyber protection, remote and automated operations will require enhanced security and proliferation controls, which have implications for operations. Such considerations are discussed in Chapter 9.
- *Design-specific operational challenges.* New reactor designs may have unique operational challenges, such as the use of molten salts and liquid fuels, as well as novel activation and waste control challenges. While this report does not explore these challenges in detail, the committee notes that assumptions about cost, operational availability, and regulatory risk need to be addressed in the development and deployment plans of any new reactor developer.
- *Regulatory inspection protocols.* As noted above, there may be potential for enhanced remote monitoring for operations, which may require or enable changes in the means for regulatory oversight. The regulatory framework needs to mirror the changes anticipated in advanced

reactor operations to ensure that opportunities for regulatory efficiency can be exploited, while maintaining current high standards.

Maintenance

Maintenance of any facility and its components is a critical element in safe operations, as well as reliability and sustainability in performance of the physical plant. Configurations of advanced reactors could include a range of designs, such as a fleet of two, four, or eight smaller reactors scaled to MWe requirements or a more conventional single-reactor design with a larger MWe output capacity. One advantage of fleet configuration is that single reactors could be removed from service to perform maintenance. However, in all cases, the balance of plant—that is, the systems that are not part of the nuclear island—would still require typical preventive and predictive maintenance, as with any other conventional contemporary plant. A skilled workforce for such maintenance work exists, and current utility companies and contractors have the personnel capacity in knowledge and numbers to maintain equipment such as steam turbine generators, high pressure piping, cooling equipment, electrical systems, control systems, and other mechanical and electrical components. Thus, it does not appear that balance-of-plant maintenance activities will present any significant complications above what the nuclear industry performs today. In fact, organizations such as EPRI and the Institute of Nuclear Power Operations (INPO) are expected to develop standards for the industry to accommodate any new configurations of reactors and on-site facilities.

FLEXIBILITY AND APPLICATIONS BEYOND ELECTRICITY

Advanced reactor systems are also being designed to provide flexibility in their energy products. These systems can be designed with the capability to produce electricity and/or process heat that can be used for industrial processes at various temperatures. Process heat could be employed to decarbonize industrial processes or heat buildings, while both electricity and heat may be required to produce synfuels or fresh water through desalination (NEA-OECD 2021). Currently operating LWRs have the proven capability to provide low-carbon, flexible electricity generation (Morilhat et al. 2019). For example, the current nuclear power plant fleet in France modifies its electricity supply over the course of a typical day or month (load following) to accommodate system demand as well as the growing variable renewable contribution within France and in neighboring interconnected countries.

Most advanced reactor designers who envision integration to the grid as the significant aspect of their operational model anticipate a future grid with a much higher fraction of renewables and therefore increased variability in revenue based on the increased variability in the demand for power from the nuclear plant. To address this challenge, many point to the ability to load follow and alter the reactor output to meet varying demands, but, as discussed further in Chapter 3, market terms that reward load following are needed to ensure continued economic viability. In the absence of such market terms, energy products in addition to electricity generation may be required for these plants to remain economically viable. See Chapter 4 for a discussion of economic considerations for advanced reactors.

Some designs may vary their power output directly, while others may use a secondary thermal storage and power generation system. For example, in the Natrium design, a 350 MWe plant may heat up a molten-salt storage system attached to a generator that can produce 500 MWe for a specific time span (5 hours), meaning that the integrated system can vary electrical power from 0 to 500 MWe. New deployment scenarios (e.g., microreactors for remote communities or off-grid applications) are also being evaluated (EPRI 2021e). A summary of these advanced reactor concepts is provided in Appendix A, and more detailed discussion of non-electric applications can be found in Chapter 5.

TECHNOLOGY PATH FORWARD

In summary, a wide range of advanced reactor technologies are currently under design and development. Industry teams are moving forward with several advanced reactor designs with a goal of demonstration and eventual commercial deployment. As discussed above, the technical readiness of these different advanced reactor design concepts varies, with some developers aiming for deployment at the end of this decade and others targeting deployment thereafter. Several technological topics must be addressed to improve the technology readiness of the advanced reactor designs under development (see Table 2-4). These reactor designs require not only further investigation of the behavior of physical phenomena (e.g., fuels and materials), but also validation by appropriate test and operational data and associated analysis. Many of the research and development approaches to these technical topics could also accelerate the time to deployment—for example, crosscutting technology programs in additive manufacturing. Compared to large LWRs, advanced reactors will likely use different deployment models, such as providing dedicated electricity to single users, process heat for industry or building heating, or heat for storage for future distribution. The non-technical challenges associated with these new deployment scenarios are addressed in subsequent chapters.

REFERENCES

Al Rashdan, A.Y., and S.W. St. Germain. 2018. *Automation of Data Collection Methods for Online Monitoring of Nuclear Power Plants*. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1475451.

ANL (Argonne National Laboratory). 2020. "Reactors Designed by Argonne National Laboratory: Fast Reactor Technology." https://www.ne.anl.gov/About/reactors/frt.shtml.

ANS Task Force (American Nuclear Society Task Force on Public Investment in Nuclear Research and Development). 2021. *The U.S. Nuclear R&D Imperative*. La Grange Park, IL: American Nuclear Society.

ARPA-E (Advanced Research Projects Agency–Energy). 2019. "GEMINA (Generating Electricity Managed by Intelligent Nuclear Assets)." https://arpa-e.energy.gov/technologies/programs/gemina.

Busby, J.T. 2009. "Economic Benefits of Advanced Materials in Nuclear Power Systems." *Nuclear Fuels and Structural Materials 2* 392(2):301–306. https://doi.org/10.1016/j.jnucmat.2009.03.018.

DOE (Department of Energy). 2009. *U.S. Department of Energy Technology Readiness Assessment Guide*. Washington, DC: Department of Energy. https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04.

DOE-NE (Office of Nuclear Energy). n.d. "Light Water Reactor Sustainability Program." Accessed November 2, 2022. https://www.energy.gov/ne/nuclear-reactor-technologies/light-water-reactor-sustainability-lwrs-program.

EPRI (Electric Power Research Institute). 2017. *Government and Industry Roles in the Research, Development, Demonstration, and Deployment of Commercial Nuclear Reactors: Historical Review and Analysis*. Program on Technology Innovation. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2019. *Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance: Topical Report EPRI-AR-1(NP)*. Technical Report. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2021a. *Nuclear Beyond Electricity—Motivating and Valuing the Flexibility of Nuclear Energy Systems*. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2021b. *Rethinking Deployment Scenarios to Enable Large-Scale, Demand-Driven Non-Electricity Markets for Advanced Reactors*. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2021c. *Advanced Reactor Materials Development Roadmap*. EPRI Report 3002022979. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2021d. *Small Modular Reactor Vessel Manufacture and Fabrication: Phase 1—Progress, Year 3*. EPRI Report 3002021037. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2021e. *Advanced Manufacturing Methods Roadmap for the Nuclear Energy Industry*. EPRI Report 3002022978. Palo Alto, CA: Electric Power Research Institute.

GIF (Generation IV International Forum). 2014. *Technology Roadmap Update for Generation IV Nuclear Energy Systems*. Generation IV International Forum.

Gohel, H.A., H. Upadhyay, L. Lagos, K. Cooper, and A. Sanzetenea. 2020. "Predictive Maintenance Architecture Development for Nuclear Infrastructure Using Machine Learning." *Nuclear Engineering and Technology* 52(7):1436–1442. https://doi.org/10.1016/j.net.2019.12.029.

Gougar, H.D., R.A. Bari, T.K. Kim, T.E. Sowinski, and A. Worrall. 2015. "Assessment of the Technical Maturity of Generation IV Concepts for Test or Demonstration Reactor Applications, Revision 2." Technical Report. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1236803.

IAEA (International Atomic Energy Agency). *Safety Related Terms for Advanced Nuclear Plants*. Vienna: International Atomic Energy Agency.

Kairos Power. 2021. "Technology." https://kairospower.com/technology.

Kunitomi, K., S. Maruyama, M. Shindoh, and Y. Sudo. 1990. "Safety Demonstration Test Plan in the High Temperature Engineering Test Reactor (HTTR) and Safety Evaluation." http://inis.iaea.org/search/search.aspx?orig_q=RN:21087989.

Morilhat, P., S. Feutry, C. Le Maitre, J. M. Favennec. 2019. "Nuclear Power Plant Flexibility at EDF." *Atw. Internationale Zeitschrift fuer Kernenergie* 64(3):131–140.

NRC (U.S. Nuclear Regulatory Commission). 10 CFR 73.54, "Protection of Digital Computer and Communication Systems and Networks," U.S. Nuclear Regulatory Commission, https://www.nrc.gov/reading-rm/doc-collections/cfr/part073/part073-0054.html.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2022. *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.

NEA-OECD (Nuclear Energy Agency Organisation for Economic Co-operation and Development). 2021. *Advanced Nuclear Reactor Systems and Future Energy Market Needs*. NEA No. 7566. Nuclear Technology Development and Economics. Paris: Nuclear Energy Agency.

Pathania, R. 2012. C*ritical Issues Report and Roadmap for the Advanced Radiation-Resistant Materials Program.* EPRI Report 1026482. Palo Alto, CA: Electric Power Research Institute.

Petti, D., R. Hill, J. Gehin, H. Gougar, G. Strydom, T. O'Connor, F. Heidet, et al. 2016. *Advanced Demonstration and Test Reactor Options Study*. INL/Ext-16-37867, Rev.2. Idaho Falls, ID: Idaho National Labatory.

Petti, D., R. Hill, J. Gehin, H. Gougar, G. Strydom, T. O'Connor, F. Heidet, et al. 2017. "A Summary of the Department of Energy's Advanced Demonstration and Test Reactor Options Study." *Nuclear Technology* 199(2):111–128. https://doi.org/10.1080/00295450.2017.1336029.

Planchon, H.P., J.I. Sackett, G.H. Golden, and R.H. Sevy. 1987. "Implications of the EBR-II Inherent Safety Demonstration Test." *Nuclear Engineering and Design* 101(1):75–90. https://doi.org/10.1016/0029-5493(87)90152-X.

Reitsma, F., M.H. Subki, J.C. Luque-Gutierrez, and S. Bouchet. 2020. *Advances in Small Modular Reactor Technology Developments: A Supplement to IAEA Advanced Reactors Information System (ARIS)*. Vienna: International Atomic Energy Agency, 2020.

Sobes, V., B. Hiscox, E.L. Popov, M.-O.G. Delchini, R. Archibald, C. Hauck, M.T. Laiu, B. R. Betzler, and K. Terrani. 2021. "Artificial Intelligence Design of Nuclear Systems Empowered by Advanced Manufacturing." *EPJ Web of Conferences* 247:06032. https://doi.org/10.1051/epjconf/202124706032.

Sowder, A. 2015. *Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design—The Liquid Fluoride Thorium Reactor (LFTR)*. Technical Report. Electric Power Research Institute. https://www.epri.com/research/products/000000003002005460.

Terrani, K.A., B.C. Jolly, M.P. Trammell, G. Vasudevamurthy, D. Schappel, B. Ade, G.W. Helmreich, et al. 2021. “Architecture and Properties of TCR Fuel Form.” *Journal of Nuclear Materials* 547:152781. https://doi.org/10.1016/j.jnucmat.2021.152781.

Viswanathan, R., J.F. Henry, J. Tanzosh, G. Stanko, J. Shingledecker, B. Vitalis, and R. Purgert. 2013. “U.S. Program on Materials Technology for Ultra-Supercritical Coal Power Plants.” *Journal of Materials Engineering and Performance* 22(10):2904–2915. https://doi.org/10.1007/s11665-013-0717-6.

WNA (World Nuclear Association). 2020. “Generation IV Nuclear Reactors.” https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx.

Zinkle, S.J., J.L. Boutard, D.T. Hoelzer, A. Kimura, R. Lindau, G.R. Odette, M. Rieth, L. Tan, and H. Tanigawa. 2017. “Development of Next Generation Tempered and ODS Reduced Activation Ferritic/Martensitic Steels for Fusion Energy Applications.” *Nuclear Fusion* 57(9):092005. https://doi.org/10.1088/1741-4326/57/9/092005.

Zinkle, S.J., K.A. Terrani, and L.L. Snead. 2016. “Motivation for Utilizing New High-Performance Advanced Materials in Nuclear Energy Systems.” *The COSSMS Twentieth Anniversary Issue* 20(6):401–410. https://doi.org/10.1016/j.cossms.2016.10.004.

3

The Evolving Electricity System and the Potential Role of Advanced Nuclear Reactors

The electric power system is undergoing its greatest and most uncertain transition yet, underpinned by many new realities, including, but extending beyond climate change. The deployment of advanced nuclear reactors could be affected by—and affect—the drivers and trajectory of this transition. Supply is changing as a new suite of low-carbon power generation technologies enter the market. Demand is also changing as more energy services (e.g., transportation and space heating) are electrified and active demand management strategies are employed. The supply and energy management options available to customers are changing, as are customers' expectations for reliability, resilience,[1] affordability, and equity. The regulatory system is evolving to address these changes and to reflect an altered economic environment. While this evolution is under way, the threats facing the aging electric power system are becoming more acute, including extreme natural events borne by climate change and physical and cyber sabotage (NASEM 2021b).

This chapter will address major drivers of change in the electricity sector and their implications for advanced nuclear technologies. Key to the discussion is a recognition that the drivers of change are interdependent, and the prominence of each is affected by location—regulations, markets, power system topology, and local attitudes play a large role in shaping the extent of the drivers for change and the speed at which changes might unfold. Moreover, these changes to the electric power system could either bolster or reduce the competitiveness of advanced nuclear power: the fact that advanced reactors are not yet commercialized makes reliable assessments of their role in the future power system difficult.

THE POTENTIAL COMPETITIVENESS OF NUCLEAR

A large suite of technologies has emerged that is altering both power supply and power demand. Most prominent among these are renewable energy systems and storage; the growth of residential and commercial energy management models like variable tariffs, smart metering, demand response, and microgrids; and the accelerating electrification of transportation, buildings, and industrial processes.

To compete in this changing electricity system, advanced nuclear power needs to be (1) affordable for owner investment without "betting the company"; (2) economically competitive with other technologies, including renewables and energy storage; (3) socially acceptable, enabling communities to accept reactor siting proposals; and (4) commercially available to utilities as they make large investments in electrification in the next few decades.

Even in future electricity grids with high deployments of wind and solar, clean, firm, generation resources will still be required. Advanced nuclear reactors could have substantial market opportunities for supplying reliable and flexible electricity generation, as well as in supporting the further expansion of the

[1] Reliability refers to designing and operating the grid so that sufficient electricity is distributed to customers in a safe and stable way. Resilience, while intertwined with reliability, refers to the ability of a system to withstand and recover from extreme events, whether owing to weather and natural events, physical sabotage, or cyber-attacks.

electrification of end uses in other sectors (transportation, buildings, and industry). The scale and speed required to achieve the full clean energy transition within challenging timescales may make it attractive to reuse existing transmission lines or other facilities that are now linked to fossil fuel thermal generators (coal and gas plants). Nuclear power could also generate electricity at high-capacity factors[2] and recover costs by serving non-grid energy needs (the focus of Chapter 5), such as the production of hydrogen. However, in each case, this is most likely to happen only *if nuclear costs are competitive with low-carbon alternatives and the other barriers to deployment discussed in this report are resolved.*

At the same time, it is important to recognize that there are multiple pathways to a reliable, decarbonized electricity system, *with or without advanced nuclear technologies*. Advanced nuclear will be competing against other forms of zero-carbon energy to provide energy, capacity, and grid stability.

THE CUSTOMER: CHANGING EXPECTATIONS

On the demand side, the “average customer” in 2030 could need and expect a host of services from the electricity system that do not exist today or would be considered niche services. Some customers want freedom of choice to pursue energy alternatives. Some desire to become completely self-sufficient and disconnected from the grid. Some customers also want to pursue renewable technologies as a commitment to contribute to the reduction in carbon emissions. Large commercial and industrial customers are responding to growing interest by their investors in environmental, social, and governance goals (BusinessWire 2020; Eckhouse 2020; Wongtrakool 2020; Venkataramani 2021; Saad 2022). These changes in customer preferences have a potentially significant impact on planning, load profiles, and grid architecture. Any movement for the design, planning, construction, and operation of new nuclear facilities must consider these elements, some of which might make new nuclear technologies attractive—if their benefits are demonstrated.

Multiple socio-technical forces are catalyzing this shift in households, chief among which is the existence and increasing affordability of a host of new distributed energy resources that enable customers to generate electricity on-site. This option once was the province of large institutional customers, such as manufacturing facilities, but is now open to individual households as well. In addition to a substantial decrease in the cost of solar photovoltaic systems and energy storage, new technologies like microturbines and hybrid battery-generator systems are emerging. Two other key technical developments are revolutions in building science and appliances that could dramatically increase energy efficiency. Attempts to decarbonize other sectors of the economy are rebounding on household energy use as well; electric vehicle charging at home is an example of a currently unfolding technological change that will increase household energy consumption and potentially stress power grids. Last, there is a shift in engagement between technologies and their users, with some demanding the ability to exert greater control over when their energy systems consume electricity. This last shift has been enabled by information and communication technologies that have made visions of smart homes possible. Individuals and households pursue these technologies for many reasons. In addition to reducing their electricity bills, some consumers seek to reduce consumption or minimize greenhouse gas emissions. There is also a growing preference among consumers for “local” economic activity, where possible, and of disentangling themselves from large corporations. Some customers are also demanding deeper social and environmental commitments from the companies they patronize. Companies are starting to recognize and respect these demands and are making ambitious social and environmental commitments, including the pursuit of net-zero emissions (Melville 2022).

Some of these trends extend beyond households and exist among commercial and industrial customers. However, the preponderance of effort among those customers has focused on ways to lower electric service bills, ensure quality power (voltage, frequency), or increase reliability. Deploying

[2] A measure of how much energy is produced by a plant compared with its maximum output. High-capacity factors reduce the per unit cost of electricity and can be an important component for a plant to recover costs and be economically viable.

generators and other electric power systems on-site enables these customers to enhance power quality or to avoid significant demand charges by shaving peak loads or shifting demand. Some have gone so far as to establish microgrids that would enable them to ride through outages without service interruption—a market that is growing rapidly (ReportLinker 2022; Technavio 2022). As extreme weather events increase in intensity and frequency, supply and demand become more variable and dynamic. The consequences of poor resilience will become more visible, as evidenced by the recent disruption at Samsung's Austin semiconductor fabrication plant, a consequence of the 2021 Texas power crisis (Carlson 2021). The extent to which future nuclear reactors, including small and microreactors, can capitalize on these trends is unclear, but worthy of analysis.

New and advanced nuclear reactors have the potential to serve smaller, more diffuse loads, which could fit well into the more decentralized generation needed under a decarbonized energy system. However, even as novel deployment models and business cases for small and micro reactors are envisioned, they will be subject to the same level of scrutiny regarding safety, reliability, affordability, and equity once a site is chosen.

THE GRID: CHANGING DEMAND AND SUPPLY, AND IMPLICATIONS FOR RELIABILITY AND RESILIENCE

Changing Demand and Supply

Both electricity demand—and the generation sources that supply this demand—are expected to change considerably between now and 2050. Customer demand for electricity will evolve owing to multiple factors, including electrification of end uses, energy efficiency improvements, production of low-carbon fuels including hydrogen, and changes in demography. These drivers affect the magnitude, shape, and flexibility of customer electricity demand, which in turn affects the use cases and business strategies of advanced nuclear technologies. They also affect how the grid should evolve.

Among these expected changes, electrification and the overall growth in demand offer the greatest market opportunity for advanced nuclear power. After over a decade of relatively flat growth in the United States, customer electricity demand is poised to increase (EIA 2021a), with electrification of new end uses being the primary contributor to this growth (see Figure 3-1). The electrification of passenger cars will drive this growth in the near term, but electrifying other end-uses, such as space heating and some industrial processes, will likely continue to boost demand well into the 2040s and 2050s, as economies seek to achieve deep decarbonization targets.

To meet this new demand, most studies forecast or demonstrate potential for significant growth in wind, solar, storage, and transmission owing to falling technology cost projections for wind, solar, and batteries (DOE 2021; Cole et al. 2021b; NAS 2020; Clack et al. 2020; Larson et al. 2020). For example, DOE's *Solar Futures Study* shows the potential for solar alone to meet more than 40 percent of electricity demand by 2050 as part of a 95 percent decarbonized grid (DOE 2021). This much solar is economically possible only because of the expected growth in diurnal storage—that is, <12 hours of discharge at rated capacity—which can shift the oversupply of daytime generation to serve evening load storage (Frazier et al. 2021). Growth in these technologies also require adequate sites, materials, manufacturing supply chains, workforce, and permitting, among other factors needed to sustain growth (DOE 2021). Low-cost natural gas—driven greatly by the increase in hydraulic fracking—has made the market penetration of alternative sources of energy generation difficult and may, in the absence of decarbonization policies, continue to pose a barrier to entry for advanced nuclear technologies. Without decarbonization policies or high fossil fuel prices, developing and deploying advanced nuclear reactors could remain difficult.

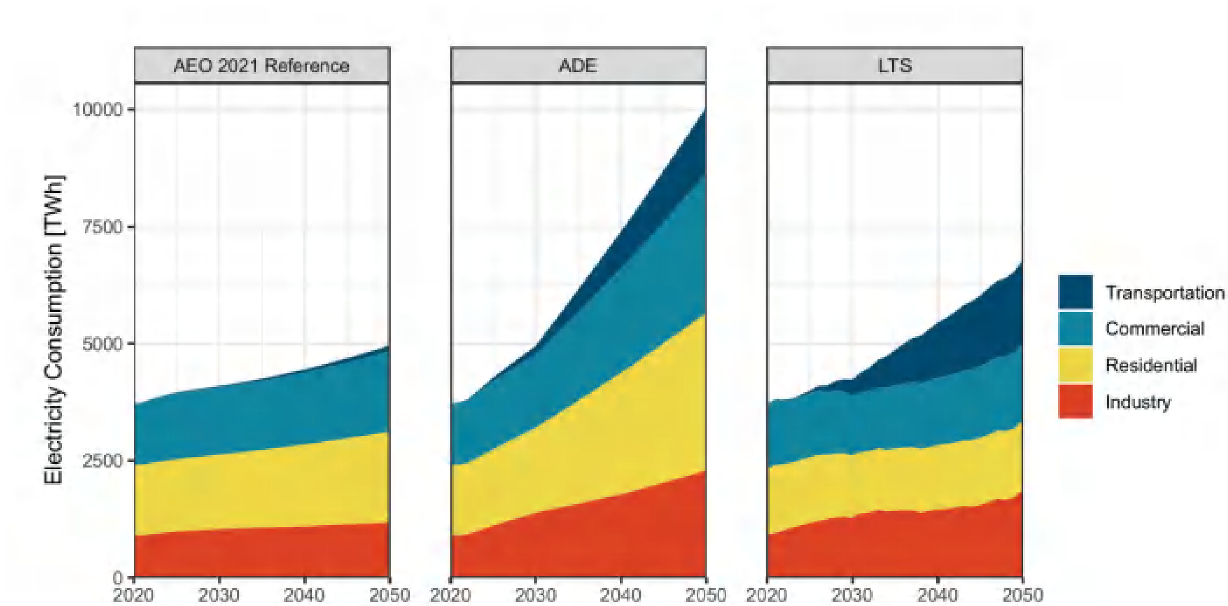

FIGURE 3-1 Potential growth trajectories for U.S. annual electricity consumption.
NOTE: AEO: Annual Energy Outlook 2021(EIA 2021); ADE: Accelerated Demand Electrification (Denholm et al 2022); LTS: Long-Term Strategy of the United States (White House 2021)
SOURCES: Committee generated, with data from Denholm, P., P. Brown, W. Cole, et al. 2022. Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf; EIA (U.S. Energy Information Administration). 2021. "Annual Energy Outlook 2021 With Projections to 2050." Washington, DC: U.S. Energy Information Administration. https://www.eia.gov/outlooks/archive/aeo21; and White House. 2021. "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050." Washington, DC: The White House. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf. P. Gagnon, M. Brown, D. Steinberg, et al., 2022, "2022 Standard Scenarios Report: A U.S. Electricity Sector Outlook," NREL/TP-6A40-84327, Golden, CO: National Renewable Energy Lab (NREL), https://doi.org/10.2172/1903762.

Estimates of the role for advanced nuclear energy in this mix is highly dependent on assumptions. A recent multi-institution study led by the Electric Power Research Institute (EPRI)—with the Environmental Protection Agency (EPA), Energy Information Administration (EIA), and National Renewable Energy Laboratory (NREL)—aimed to understand how model structures and input assumptions affect nuclear energy in long-term planning models (EPRI 2022). The assumptions with the greatest impact on nuclear deployment were policies and technology cost. The model comparison showed that decarbonization policies support existing nuclear generation but are not sufficient to support significant new nuclear builds in the absence of significant cost reductions or a nuclear technology carveout.

The EPRI study is consistent with many recent studies that show significant growth for new nuclear to meet grid needs[3] when certain conditions are met:

- *Nuclear costs are substantially lower than those experienced recently in the United States* (~$2,000–$4,000/kW). In this case, nuclear is competitive regardless of other factors such as

[3] These studies did not optimize nuclear deployment to include meeting non-grid energy demands. These opportunities are discussed in Chapter 5.

decarbonization policies, timing of advanced nuclear's commercial availability, and assumptions about renewable energy (RE) and natural gas competitiveness (EPRI 2018, 2022; Cole 2021b; Larson et al. 2021; IEA 2022).

- *Highly constrained growth of RE and transmission owing to issues such as supply chain or land availability, which in turn increases overall system cost, enabling nuclear energy to be competitive at higher costs* (e.g., ~$5,500/kW, depending on assumptions). These conditions also assume commercial availability starting in 2035 (or sooner) and stringent decarbonization policies (Larson et al. 2021; Denholm et al. 2022).
- *Limitations on availability of other technologies that provide capacity* (e.g., no biofuels, hydrogen, CCS, or long-duration energy storage) assuming decarbonization policies and $4,000–$6,000/kW nuclear costs (Brown and Botterud 2021).

Long-term capacity expansion models such as featured in the EPRI study do not alone address the full suite of questions related to power system planning. Future market and generation capacity expansion models include many uncertainties and are highly dependent on model formulation, cost assumptions, and policy evolution. No model can account for the full range of possible scenarios and non-economic attributes. For example, the Los Angeles 100% Renewable Energy (LA100) study (Cochran and Denholm et al. 2021) employed more than 15 models to evaluate reliability, distribution grid interactions, and environmental justice, among other questions that are central to planning.[4]

Broadly, studies show that while nuclear capital costs are an important driver for nuclear's deployment, there remain situations in which nuclear generation can be competitive. For example, a more uncertainty-oriented approach would incorporate aspects of "real options" that value the future trajectory of technology options and ensure that options are not prematurely eliminated from consideration. While the approach may ultimately not yield decisions to deploy nuclear as a low-carbon alternative, it would properly reflect the value that is inherent in maintaining flexibility in grid expansion decision making (Caunhye et al. 2022). Balanced approaches to decarbonization that incorporate a wide variety of technologies can also spread risk across multiple supply chains and limit challenges in integration (IEA 2021; Brick and Thernstrom 2016).

Finding 3-1: Electrification owing to economy-wide decarbonization presents a significant market opportunity for advanced nuclear generation to serve the grid, particularly if its widespread commercial availability occurs when utilities are scaling up infrastructure to respond to this demand. Nuclear's competitiveness to serve this new demand is sensitive to cost projections. Models suggest that advanced nuclear will likely be competitive if sufficiently low costs are achieved (e.g., $2,000–$4,000/kW) regardless of other conditions. Advanced nuclear could also achieve significant growth at higher cost ranges (e.g., ~$4,000–$6,000/kW) if other power system costs are higher than expected (e.g., owing to limited transmission growth or limited materials) or there is growing demand for non-electricity products (e.g., hydrogen).

[4] LA100 evaluated scenarios to 100% RE in which the utility retains its Arizona-based nuclear generation. While nuclear does provide capacity during normal operations and helps offset the need for new RE supply, its distance from the load center and reliance on transmission means that this source of generation might not be available for LA's critical contingency planning events, such as multiple transmission outages owing to earthquakes or wildfire mitigation. Instead, the LA100 study meets adequacy requirements in LA by building local sources of firm capacity (e.g., hydrogen- or biofuel-combustion turbines). LA100 serves as an example of how a location-specific analysis can better capture transmission and operational constraints that require simplification in national studies.

Implications for Reliability

In a more electrified economy, grid reliability is paramount. The changing grid, especially the growth of inverter-based technologies[5] on both the bulk power and distribution grids, raises questions about how to maintain and strengthen reliability and how to create regulations and market signals that incentivize attributes needed for reliability, at both investment and operating timescales.

The North American Electric Reliability Corporation (NERC) defines reliability in terms of two aspects: adequacy and operating reliability.[6] Adequacy is the ability of the electric system to always supply and deliver the aggregate electric power requirements of electricity consumers, considering scheduled and reasonably expected unscheduled outages of system components. Operating reliability, meanwhile, is the ability of the electric system to withstand sudden disturbances, such as electric short circuits or unanticipated loss of system components (NERC 2007).

Resource Adequacy

The combination of wind and solar could contribute to the bulk of low-carbon generation, with batteries especially useful at shifting the supply of daytime generation to meet evening demand. But these technologies are not currently cost-effective to meet demand throughout the year (Cole et al. 2021a). During periods of low wind and solar, or periods of high demand, planners must look to sources of firm capacity. Low-carbon electricity generation options include hydropower, nuclear, geothermal, fossil with carbon capture, biofuels, fuels produced from low-carbon electricity, such as hydrogen, and demand response options. These options each have their own constraints but are among the options that utilities are considering today. *During periods when wind, solar, and batteries cannot contribute to the system in sufficient quantities, these alternative sources can become competitive, even if they are not otherwise (or generally) competitive based on levelized cost of energy.*

Nuclear generation, with its near year-long availability (typically), could help meet energy needs during periods of especially low renewable power production or high demand, but would likely provide above market-clearing price electricity during most of the year in a system with significant deployment of wind and solar. Wind and solar have limited operating costs and thus are typically dispatched first. However, nuclear energy could still be competitive depending on cost projections, further projected increases in load, or if nuclear secures additional sources of revenue for its excess heat or electricity production (Box 3-1).

BOX 3-1
Why Might Nuclear Generation Be Competitive Even If Its Levelized Cost of Energy Is Not?

Levelized cost of energy (LCOE) is used as a metric of the cost of energy produced ($/MWh), a reflection of total costs to total generation. However, the value of energy produced is not the same at all times of the year, and its value varies by location. The value of generation to a total system reflects its contribution to energy and reliability—that is, the value of *energy, capacity, and ancillary services* at specific points of time and location. System value will change over time to reflect changes to demand, generation, transmission, operations, markets, and other factors. Nuclear's competitiveness in a particular power system will depend on factors that reflect total system value and its cost of generation.[a]

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[5] Technologies such as wind and solar generators and batteries produce DC power. They are connected to the grid via power electronic inverters and are referred to as inverter-based technologies. Inverters convert DC power to AC power at 60 Hz, which is compatible with electrical grids in the United States.

[6] All bulk power system owners, operators, and users must comply with NERC-approved mandatory reliability and critical infrastructure protection standards. NERC and FERC continuously monitor the bulk electric system and severe fines and penalties are imposed for violations (NERC 2007).

In a low-carbon system, high-capacity value occurs when wind, solar, and batteries are insufficient to meet demand—for example, during periods in which demand soars because of a heat wave or when wind and solar generation are especially low for extended periods. Ensuring a reliable supply of electricity for such periods has always been expensive—today's systems typically use gas peaker plants. In a low-carbon system, the timing of these "peak" needs will change based on variable supply as well as new threats to the grid based on the changing climate. These periods of concern require supply at specific times and in specific locations. Nuclear generation could lower system costs if its overall contribution to peak and non-peak events—a combination of its energy and capacity value—is lower than alternative portfolios of technologies.[b]

[a] For more details on how to consider alternative metrics to LCOE, see T. Mai, M. Mowers, and K. Eurek, 2021, "Competitiveness Metrics for Electricity System Technologies," NREL/TP-6A20-72549, Golden, CO: National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy21osti/72549.pdf.

[b] The value of ancillary services is typically much smaller than energy and capacity value (Denholm et al. 2019).

Operating Reliability

Operating reliability addresses the capabilities needed to maintain voltage and frequency, provide system protection, and recover from disturbances. Synchronous generators were at one point considered essential to grid reliability, but inverter technology has advanced considerably over the past decade and already exceeds the performance of synchronous generators in maintaining grid frequency if the underlying energy is available (EPRI 2019; Loutan et al. 2017). More recent advances have centered on the inverters evolving from grid-following to grid-forming technologies, in which they actively and autonomously control frequency and voltage. For example, a portfolio of research is exploring how grid-forming inverters can black-start a system (restoring a power system after an outage without relying on a broader transmission grid) and provide other services (Sajadi et al. 2022; Lin et al. 2020; Lasseter et al. 2020). Continued technological and cost advances in inverter technologies could enable a new class of technologies to provide the full range of essential grid services. These changes, in turn, would affect the value of grid services and methods to incentivize their provision.

While these grid-forming technologies have been demonstrated at the device and plant levels, the grid is not yet prepared to operate completely on inverter-based resources. However, given the significant growth expected of inverter-based technologies, many of the questions about the technology will need to be addressed in the coming decade, in advance of the commercial availability of advanced nuclear generation.[7] For example, Maui will soon be able to supply its 70,000 customers with 100 percent inverter-based generation for many hours of the year as early as 2023 (Hoke 2020). Larger grids such as ERCOT and Ireland have already managed 66 percent and 70 percent instantaneous inverter-based generation levels, respectively, through combinations of approaches including grid-forming inverters, synchronous condensers, and demand-side response (Matevosyan et al. 2019).

The role of advanced nuclear generation in providing essential grid services beyond the provision of energy (e.g., providing voltage and frequency stability) could come down to a question of cost in comparison to both inverter-based and non-inverter technologies such as synchronous condensers, fossil with CCS, or combustion turbines fueled by renewables or other low-carbon resources. In addition, the extent to which grid-forming inverters do not just mimic the characteristics of synchronous generation but

[7] Remaining questions include how operations can be maintained with a mix of grid-following and grid-forming inverters; how the programmed inverter controls can be coordinated so that they do not counteract each other and raise new stability impacts; and how to evolve black start strategies from today's top-down, serial-restoration approach to a bottom-up, parallel inverter-based approach in the future (Gevorgian 2020). In parallel, grid codes and market designs will need to be revisited as approaches evolve.

establish a completely new approach to grid stability that focuses on inverter characteristics could also affect the need and market value for nuclear capabilities.[8]

> Finding 3-2: Grid reliability is paramount in an increasingly electrified economy, and a broad range of low-carbon technologies are currently available—or soon will be—to support reliability, both resource adequacy and operating reliability. On resource adequacy, advanced nuclear power can provide the high-value, low-carbon energy needed when wind, solar, and batteries are unavailable, but its overall economic competitiveness depends on the value of its (grid or non-grid) energy at other times of the year. Regarding operating reliability, advanced nuclear will be competing with many technology types—conventional and inverter-based—to offer grid services such as voltage and frequency stability. While the grid is not yet prepared to operate solely on inverter-based resources today, reliability solutions have the potential to evolve rapidly to match the growing deployment of inverters. These advancements, which could occur before commercial availability of advanced nuclear, could affect the market value for nuclear power to provide essential grid services.

Resilience

The climatic, technological, and political forces that are remaking the electric power system will have profound repercussions on how to assess and ensure system resilience. Resilience is interrelated but distinct from reliability. Where reliability focuses on what is needed to keep the grid operational through different kinds of events (e.g., generation or transmission outage, surge in demand), resilience focuses on how to recover from an event in which power is disrupted. More specifically, resilience is the ability to prepare for and adapt to changing conditions, maintain critical service during times of disruption, and recover rapidly from disruptions, including deliberate attacks, accidents, or naturally occurring threats or incidents (Figure 3-2).

Growing fears of cyber-physical disruption and extreme weather events have led to an increased focus on resilience in the past two decades. For example, every 2 years, the North American Electric Reliability Corporation (NERC), under its Information Sharing and Analysis Center (E-ISAC), conducts high-level virtual event tests—known as GridEX—to test the response and recovery plans of participating organizations in the face of events that disrupt the grid (such as extreme weather) or simulated cyber or physical attacks.

[8] A system with high levels of inverter-based generation will require different controls compared to a system based on synchronous generators owing to the underlying differences in dynamics. There could be conditions in which operational security and stability is more easily provided exclusively by grid-forming inverters that adjust to real-time settings than by a mix of grid-forming and synchronous generators (Sajadi et al. 2022).

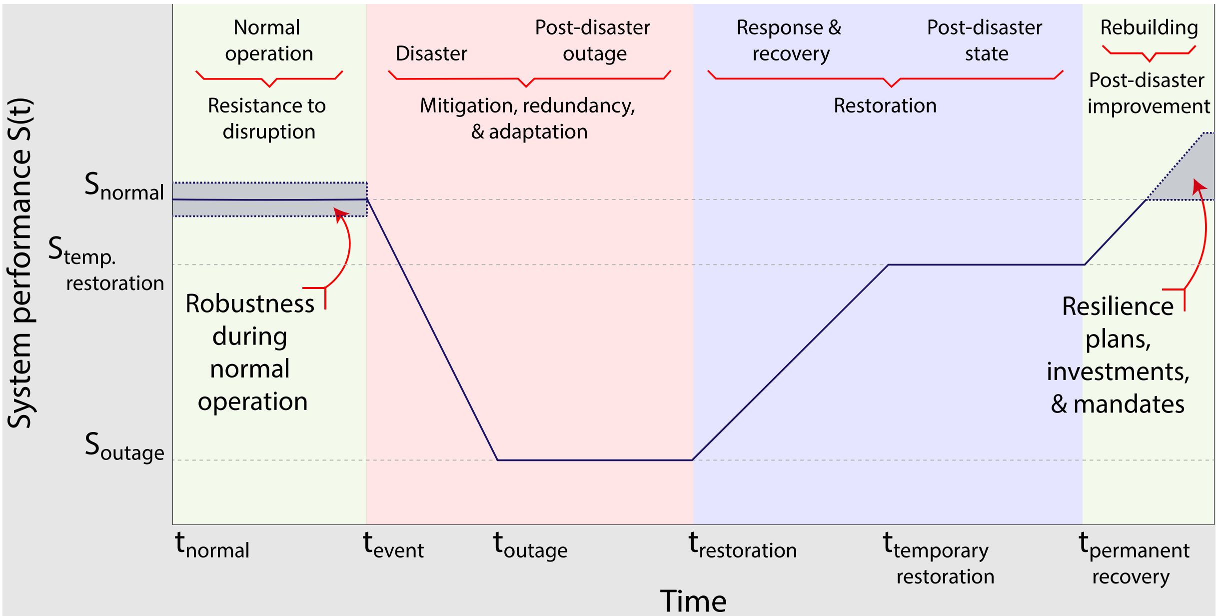

FIGURE 3-2 Enhancing electric power system resilience requires planning and investments that ensure disruptions are resisted; their extent and consequences are mitigated; and that response, recovery, and restoration are accelerated.

The discussion about resilience among utilities has nothing to do with choosing a specific generator type. Improving power system resilience requires expensive, laborious, and coordinated implementation of strategies that are "in the weeds" (NASEM 2017). Resilience requires extensive preparation—rarely at the level of generators, which are already highly resilient, but at other levels of the power system, and must involve investments in grid hardening, fuel storage, situational awareness, and the deployment of distributed energy resources (Campbell 2012) and advanced grid operations. In each case, site-specific considerations are of paramount importance, and have much more to do with standard operating procedures regarding vegetation management cycles and rapid post-disaster access to sites than they do with the choice of a specific generator. Nuclear reactors, like most generators, are generally resilient to weather events (NEI 2018). For example, in 2018, all but 1 of the 20 reactors in Hurricane Florence's path across the Carolinas, Georgia, and Virginia remained operational at full power throughout the storm. However, as climate change increases the intensity of severe weather events, nuclear power plants, like most generators, will be tested to new extremes (Jordaan et al. 2019; Ahmad 2021). For example, in the recent Texas storm of 2021, inadequate weatherization of feedwater pumps required one of the nuclear units at the South Texas Project to go offline (World Nuclear News 2021), and France cut nuclear production at several plants during July and August 2022 heat waves owing to excessive cooling water temperatures. The 10 biggest blackouts in U.S. history have occurred within the past 30 years, and half of those in the past decade. The frequency and severity of these events is expected to increase as climate breakdown continues.

Finding 3-3: At the moment, investors rarely focus on resilience in choosing among generators, except in highly constrained environments, because generators are relatively more resilient components of the grid. When it comes to enhancing power system resilience, utilities focus on the transmission and distribution system because they are more vulnerable to damage.

Recommendation 3-1: A forum similar to GridEX should be established by vendors, utilities, and industry support organizations, with the active participation of experts from the Departments of Energy and Homeland Security, to elaborate any additional risks that

emerge owing to novel reactor deployment paradigms—such as placing reactors in industrial parks, underground, at sea, or in close proximity to multiple other modules, or controlling them remotely—and develop rules, guidelines, and standard operating procedures for reactor operators that ensure nuclear power's continued resilience and that seek to capitalize on the proposed versatility of advanced nuclear reactors.

THE REGULATORS: PRICING AND REGULATORY REFORM WILL AFFECT NUCLEAR COMPETITIVENESS

The evolution of the grid will necessitate the development of new regulatory regimes and rate structures to adequately manage the grid and maintain public infrastructure. There are constant interactions among the physical elements of the grid, information and communications technologies, and organizational aspects. Changes in one aspect require changes in the others, and grid evolution is already leading to increased investment in grid technologies, digitization, data analytics, distribution system sensing and monitoring, and controls to enhance operational efficiency and to integrate new resources.

Grid operators and utilities are carefully considering what reforms may be necessary in wholesale energy and ancillary service markets to maintain reliability and resiliency. To address these issues, the Federal Energy Regulatory Commission (FERC) has been conducting a series of technical conferences focused on reforms that modernize electricity market design, including critical questions regarding the nature and timing of such reforms. There is growing recognition that balancing a grid with generation and load that are both increasingly variable requires incentivizing operational flexibility and firm capacity. If new and advanced reactors prove small and versatile in their ability to load-follow, these market reforms would help the competitiveness of nuclear resources.

A white paper prepared by the FERC staff (Docket No. AD21-10-000) states that Regional Transmission Organizations (RTO) or Independent System Operators (ISO) have increasingly had to rely on out-of-market actions (e.g., manual commitments, posturing, load biasing) to address the limitations of conventional RTO/ISO market design and manage resource variability owing to insufficient levels of operational flexibility. These out-of-market approaches can undermine price formation in energy and ancillary service markets and reduce incentives for investments in the flexible resources needed to manage operational uncertainty. RTOs/ISOs are adopting different market reforms to address the expected operational challenges associated with the changing customer resource mix and load profiles. To address these challenges, FERC leadership is focusing on three prime issues: "how system needs are changing; how those changing services are being procured in organized markets; and the best way to price products and services" (FERC 2021).

Regulatory Reform

Regulation plays a key part in how the electric power system will evolve, and it continues to be stimulated by major energy legislation. Congress has recently passed the bipartisan Investment and Jobs Act (Infrastructure Law) and the Inflation Reduction Act (IRA). Together, these laws will help fund the rebuilding of critical infrastructure and enhance investment in clean energy to tackle the growing threat of climate change. The Infrastructure Law provides more than $65 billion to upgrade power infrastructure in the United States by funding the addition of thousands of miles of new transmission that could help integrate clean energy technologies. This law also provides $7.5 billion to build out a national electric vehicle (EV) charging network; $65 billion for high-speed Internet through broadband infrastructure deployment; and $50 billion to make the electricity infrastructure more resilient to the impacts of climate change weather events and cyber-attacks.

On the regulatory front, FERC, electricity market operators (i.e., RTOs/ISOs), federal power marketing entities, public power utilities, and state regulatory commissions play a vital role in the development and enhancement of the electric transmission system. The National Academies in its recent publication *The Future of Electric Power in the United States* emphasizes the need for "support across the government for the evaluation, planning and siting of regional transmission facilities in the U.S." (NASEM 2021).

Along those lines, FERC has recently issued a Notice of Proposed Rulemaking (NOPR) in Docket No. RM21-17 addressing regional transmission planning and cost allocation. This NOPR can encourage greater dialogue involving FERC, DOE, the Department of Interior, state commissions, utilities, other transmission providers, RTOs/ISOs, and other key stakeholders.

FERC has stressed in the NOPR that robust, well-planned transmission system is foundational to ensuring an affordable and reliable supply of electricity. FERC has also supported a joint state/federal board to address the broad array of issues surrounding cost allocation and siting issues. It is hoped that these two major initiatives will jumpstart the expansion of transmission to integrate advanced new nuclear and other evolving technologies.

Despite the accomplishments of past legislation and regulation, the regulatory process is slow; it cannot respond to rapid changes in technology and changing customer expectations. Greater informal collaborations are needed to expedite and improve critical decision-making in areas of particular concern. The regulatory and economic environment needs to encourage innovation and seek to mitigate rather than expand risks that arise from uncertainty in the regulatory process. The structures of the electricity system in the United States limit what is achievable through action at the federal level, and thus the states are vital laboratories for experimentation and implementation.

States with renewable mandates have changed their supply mix. Over the past 8 years, more than half of new electricity generation capacity was wind and solar. With these developments, the grid is becoming more transactive[9] at both the wholesale and retail level. This direction is clear from a recent landmark FERC Order 2222, which allows distributed energy sources at the retail level to be aggregated and participate in wholesale electricity markets on the same basis as utility power plants (see Box 3-2 for additional details).

BOX 3-2
FERC Order 2222 and DER

FERC Order 2222 could cause a paradigm shift from a major reliance on traditional generation sources such as coal, oil, nuclear power, or natural gas primarily owned by utilities to broader market participants with an expanded array of clean energy sources. The rule enables distributed energy resources (DERs)—small-scale power generation or energy storage technologies from 1 kW to 10,000 kW—to participate in organized markets alongside traditional resources in the regional wholesale markets through aggregations. To facilitate this outcome, regional grid operators must revise their tariffs to establish DERs as a category of market participant. These tariffs will allow the aggregators to register their resources in more than one organized market that can accommodate the physical and operational characteristics of those resources. This will require detailed coordination between RTO/ISOs and DSOs. FERC Order 2222 is good news for new, advanced modular reactors if they can qualify as DERs and provide capacity at competitive levelized costs of energy. Additional reforms in organized markets may be necessary for new nuclear to be competitive on the evolving grid.

A recent report by Poudel et al. (2021) examined how small and advanced reactors could be integrated in a distributed fashion to provide benefits to the grid under the context of FERC Order 2222.

[9] The National Institute of Standards and Technology defines transactive energy as "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter" (NIST 2017).

First, there are critical applications for which these reactors might be appropriate, like military facilities. Second, these reactors might be able to alleviate the need for enormous investments in new transmission infrastructure if they are deployed at problematic nodes along the power grid that are especially congested. Otherwise, transmission congestion would make it difficult to transmit electric power produced from renewable generators to load. This could become especially important as the demand profile changes radically owing to the electrification of vehicles and buildings, as well as the demand-side management strategies. It will not be economic to upgrade the transmission network to handle peak loads in each case and adopting mitigating measures like dynamic pricing—while very useful—can only go so far in resolving this problem.

Third, small reactors could participate in virtual power plants (VPPs) with a hybrid mix of generation technologies. This solution could alleviate issues related to siting reactors very close to communities operating VPPs. VPPs do not have a physical boundary but rather aggregate and coordinate generators, storage, and loads within the distribution system to provide power and ancillary services to the grid. In addition to providing congestion relief, such VPPs can also provide ancillary services such as reactive power support, frequency regulation, secondary and tertiary frequency control, and load following. Continuous coordination with the distribution system operator (DSO) and transmission system operator (TSO) is critical to optimizing VPP operation.

> Finding 3-4: Federal Energy Regulatory Commission Order 2222 opens the door for small and advanced reactors to have their output aggregated to serve evolving electricity markets. These reactors, if located on congested transmission nodes, could alleviate the need for new transmission.

Pricing Reform

There also is an urgent need for pricing reform both with respect to wholesale bulk power markets and retail electricity markets. At the wholesale level, particularly in organized markets, the minimum price offers may not be sufficient to sustain the operation of some existing nuclear facilities, let alone new and advanced nuclear facilities.

State regulators and/or RTOs and ISOs support flexible rate structures—including performance ratemaking and other approaches that consider changing customer preferences, loads, power supply mix, and demographics. This new direction could enhance the prospects of nuclear power, particularly with its high historic capital cost. Some nuclear plants in the PJM Interconnection[10] were forced to shut down because they were unable to meet the price level that could sustain their base load operation in view of declining renewable energy and natural gas prices. Externalities such as the social cost of carbon are not explicitly considered in wholesale pricing models, so even though nuclear is playing a significant role in avoiding carbon emissions, it is not afforded clean energy priority consideration in organized power markets. That said, any developments that serve to recognize the value of low-carbon energy would benefit a wide range of technologies.

Nuclear power's carbon-free benefits are typically not priced in today's markets, so the value of nuclear cannot properly be valued using market prices only. This can send unclear signals to plant owners about how to best manage lifetimes of existing nuclear plants. To address this challenge, both New York and Illinois have given nuclear priority status in their markets in view of its benefits in carbon reduction and role in maintaining reliability. The IRA provides tax credits for energy produced from existing nuclear, which can extend the useful life and enhance the competitiveness of baseload nuclear facilities. It

[10] The PJM Interconnection is a Regional Transmission Organization within the Eastern interconnection grid. PJM operates an electric transmission system serving all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia.

also provides new tax credits to stimulate the development of advanced new nuclear. Changes also are needed in retail electricity markets. Electricity demand must be more price responsive, so state commissions should establish time variant tariffs that encourage more efficient use of electricity, as well as performance-based rates. A small percentage of retail consumers can see and respond to real-time prices and changes in energy system conditions. It is important for utilities to probe new rate designs to enhance the relationship with the customer by putting less emphasis on increased usage (sales) to increased breadth and variety of electricity services (electrification).

Finding 3-5: Regional Transmission Operators (RTOs) want to integrate more low-carbon electricity generation resources. The Inflation Reduction Act adds/modifies various clean energy tax provisions in the Internal Revenue Code, which will expand the participation of clean energy technologies, including existing and advanced new nuclear, in wholesale, bulk power markets and retail electricity markets.

Recommendation 3-2: The Federal Energy Regulatory Commission (FERC) should continue to examine approaches to improve the Minimum Offer Price Rule (MOPR) to better value generation sources, like nuclear, that can provide resilience, reliability, and low-carbon benefits. FERC should conduct additional workshops and technical conferences to discuss the development of clearer rules and price signals for clean generation and the capabilities provided by existing and evolving nuclear plants. In making changes to the MOPR, FERC should consider provisions in the Inflation Reduction Act that provide for existing nuclear to receive credits (Zero Emissions Nuclear Facilities Credit) for electricity produced after 2023 and before 2033 and consider legislation adopted in New York and Illinois that recognizes the value of existing nuclear. Last, FERC should consider the potential future impact of a broad range of new and expanded tax credits that apply to new nuclear, renewables, energy storage, hydrogen, and other clean energy technologies that serve electricity markets.

REFERENCES

Aborn, J., E. Baik, S. Benson, A.T. Bouma, J. Buongiorno, J.H. Lienhard, J. Parsons, and Q.J. Wei. 2021. "An Assessment of the Diablo Canyon Nuclear Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Production." Presentation. Stanford University Precourt Institute of Energy. http://scientificintegrityinstitute.org/MITDiabloPPT031622.pdf.

Abraham, S. 2003. *National Transmission Grid Study*. https://doi.org/10.2172/1184312.

Ahmad, A. 2021. "Increase in Frequency of Nuclear Power Outages Due to Changing Climate." *Nature Energy* 6(7):755–762. https://doi.org/10.1038/s41560-021-00849-y.

ASCE (American Society of Civil Engineers). 2021. "2021 Report Card for America's Infrastructure." https://infrastructurereportcard.org/wp-content/uploads/2020/12/Energy-2021.pdf.

Bills, G. 2021. "Turbine Lifetime Limits Require a Reality Check." *IJGlobal*, July 30. https://www.ijglobal.com/articles/157132/turbine-lifetime-limits-require-a-reality-check.

Bistline, J. 2021. *Powering Decarbonization: Strategies to Achieve Net-Zero Emissions in the Electric Sector and Beyond*. Palo Alto, CA: Electric Power Research Institute.

Brick, S. and S. Thernstrom. 2016. "Renewables and Decarbonization: Studies of California, Wisconsin and Germany." *Electricity Journal* 29:6–12.

Brown, P., and A. Botterud. 2021. "The Value of Inter-Regional Coordination and Transmission in Decarbonizing the U.S. Electricity System." *Joule* 5(1).

BusinessWire. 2020. "NRG Energy Becomes First North American Company to Issue Sustainability-Linked Bond." *BusinessWire*, December 9. https://www.businesswire.com/news/home/20201209005550/en/NRG-Energy-Becomes-First-North-American-Company-to-Issue-Sustainability-Linked-Bond.

Callegari, C., A. Szklo, and R. Schaeffer. 2018. "Cost Overruns and Delays in Energy Megaprojects: How Big Is Big Enough?" *Energy Policy* 114(March): 211–220. https://doi.org/10.1016/j.enpol.2017.11.059.

Campbell, R.J. 2012. *Weather-Related Power Outages and Electric System Resiliency*. R42696. Washington, DC: Congressional Research Service.

Capka, J.R. 2006. "Financing Megaprojects." *Public Roads* 69(4). https://trid.trb.org/view/778736.

Carlson, K. 2021. "Shutdown of Austin Fab During Freeze Cost Samsung at Least $268 Million." *Austin American-Statesman*, April 30. https://www.statesman.com/story/business/2021/04/30/austin-fab-shutdown-during-texas-freeze-cost-samsung-millions/4891405001.

Caunhye, A.M., M.-A. Cardin, and M. Rahmat. 2022. "Flexibility and Real Options Analysis in Power System Generation Expansion Planning Under Uncertainty." *IISE Transactions* 54(9):832–844. https://doi.org/10.1080/24725854.2021.1965699.

Clack, C.T.M., A. Choukulkar, B. Coté, and S.A. McKee. 2020. *Why Local Solar for All Costs Less: A New Roadmap for the Lowest Cost Grid*. Boulder, CO: Vibrant Clean Energy.

Cole, W.J., D. Greer, P. Denholm, A.W. Frazier, S. Machen, T. Mai, N. Vincent, and S.F. Baldwin. 2021a. "Quantifying the Challenge of Reaching a 100% Renewable Energy Power System for the United States." *Joule* 5(7):1732–1748. https://doi.org/10.1016/j.joule.2021.05.011.

Cole, W.J., V. Carag, M. Brown, P. Brown, S. Cohen, K. Eurek, W. Frazier, et al. 2021b. *2021 Standard Scenarios Report: A U.S. Electricity Sector Outlook*. Technical Report NREL/TP-6A40-80641. Golden, CO: National Renewable Energy Laboratory.

Denholm, P., D.J. Arent, S.F. Baldwin, D.E. Bilello, G.L. Brinkman, J.M. Cochran, W.J. Cole, et al. 2021. "The Challenges of Achieving a 100% Renewable Electricity System in the United States." *Joule* 5(6):1331–1352. ISSN 2542-4351. https://doi.org/10.1016/j.joule.2021.03.028.

Denholm, P., Y. Sun, and T. Mai. 2019. *An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind.* NREL/TP-6A20-72578. Golden, CO: National Renewable Energy Laboratory.

DOE (Department of Energy). 2021. "Solar Futures Study." https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf.

DOE-CESER (Office of Cybersecurity, Energy Security, and Emergency Response). 2021. *State of Florida—Energy Sector Risk Profile*. Department of Energy. https://www.energy.gov/sites/default/files/2021-09/Florida%20Energy%20Sector%20Risk%20Profile.pdf.

DOE-EERE (Office of Electricity Delivery and Energy Reliability). 2013. *Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure*. Washington, DC: Department of Energy.

Eckhouse, B. 2020. "JetBlue First Airline to Line Up Sustainability-Linked Loan." *Bloomberg Green*, February 24. https://www.bloomberg.com/news/articles/2020-02-24/jetblue-first-airline-to-line-up-sustainability-linked-loan.

EIA (U.S. Energy Information Administration). 2021a. *Annual Energy Outlook 2021*. Washington, DC: U.S. Energy Information Administration.

EIA. 2021b. *Battery Storage in the United States: An Update on Market Trend*s. Washington, DC: U.S. Energy Information Administration.

EPRI (Electric Power Research Institute). 2018. *Exploring the Role of Advanced Nuclear in Future Energy Markets: Economic Drivers, Barriers, and Impacts in the United States*. 3002011803. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2019. *Meeting the Challenges of Declining System Inertia*. Technical Update 3002015131. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2022. *Nuclear Energy in Long-Term System Models: A Multi-Model Perspective*. Technical Update 3002023697. Palo Alto, CA: Electric Power Research Institute.

FERC (Federal Energy Regulatory Commission). 2021. “Technical Conference Regarding Energy and Ancillary Services Markets.” https://ferc.gov/news-events/events/technical-conference-regarding-energy-and-ancillary-services-markets-09142021.

Flyvbjerg, B. 2014. “What You Should Know About Megaprojects and Why: An Overview.” *Project Management Journal* 45(2):6–19. https://doi.org/10.1002/pmj.21409.

Form Energy. 2020. *Best Practice Modeling to Achieve Low Carbon Grids: Why Today’s Grid Planning Tools Fall Short and How New Approaches Can Lower Electric Costs and Increase Reliability*. https://formenergy.com/wp-content/uploads/2020/12/Form-Energy-4Q2020-Best-Practice-Modeling-whitepaper-12.21.20.pdf.

Frazier, A.W., W. Cole, P. Denholm, S. Machen, N. Gates, and N. Blair. 2021. *Storage Futures Study: Economic Potential of Diurnal Storage in the U.S. Power Sector*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77449.

Freeman, G.M., J. Apt, and J. Moura. 2020. “What Causes Natural Gas Fuel Shortages at U.S. Power Plants?” *Energy Policy* 147(December):111805. https://doi.org/10.1016/j.enpol.2020.111805.

Freeman, G.M., J. Apt, S. Blumsack, and T. Coleman. 2021. “Could On-Site Fuel Storage Economically Reduce Power Plant-Gas Grid Dependence in Pipeline Constrained Areas like New England?” *Electricity Journal* 34(5):106956. https://doi.org/10.1016/j.tej.2021.106956.

Garemo, N., S. Matzinger, and R. Palter. 2015. “Megaprojects: The Good, the Bad, and the Better.” *McKinsey & Company*, July 1. https://www.mckinsey.com/business-functions/operations/our-insights/megaprojects-the-good-the-bad-and-the-better.

Gevorgian, V. 2020. “Energy Transition and Reliability Challenges in Modern Power Grids.” https://www.nrel.gov/docs/fy20osti/75143.pdf.

Hirsch, A., Y. Parag, and J. Guerrero. 2018. “Microgrids: A Review of Technologies, Key Drivers, and Outstanding Issues.” *Renewable and Sustainable Energy Reviews* 90(July) 402–411. https://doi.org/10.1016/j.rser.2018.03.040.

Hoke, A. 2020. “Power HIL Evaluation of Inverter Controls for 100% Inverter-Based Bulk Power Systems.” Power Electronic Grid Interface (PEGI) Platform Workshop. October 13. https://www.nrel.gov/aries/assets/pdfs/pegi-hoke.pdf.

IEA (International Energy Agency). 2021. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Paris: International Energy Agency.

IEA. 2022. *Nuclear Power and Secure Energy Transitions: From Today’s Challenges to Tomorrow’s Clean Energy Systems*. Paris: International Energy Agency.

ISO-New England. n.d. “Natural Gas Infrastructure Constraints.” https://www.iso-ne.com/about/what-we-do/in-depth/natural-gas-infrastructure-constraints.

Jadun, P., C. McMillan, D. Steinberg, M. Muratori, L. Vimmerstedt, and T. Mai. 2017. *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections Through 2050*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-70485. https://www.nrel.gov/docs/fy18osti/70485.pdf.

Jordaan, S.M., A. Siddiqi, W. Kakenmaster, and A.C. Hill. 2019. “The Climate Vulnerabilities of Global Nuclear Power.” *Global Environmental Politics* 19(4):3–13. https://doi.org/10.1162/glep_a_00527.

Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, S. Pacala, et al. 2020. *Net-Zero America by 2050: Potential Pathways, Deployments, and Impacts*. Princeton, NJ: Princeton University Press.

Lasseter, R.H., Z. Chen, and D. Pattabiraman. 2020. “Grid-Forming Inverters: A Critical Asset for the Power Grid.” *IEEE Journal of Emerging and Selected Topics in Power Electronics* 8(2):925–935. https://doi.org/10.1109/JESTPE.2019.2959271.

Lee, A. 2014. “Northeast and Mid-Atlantic Power Prices React to Winter Freeze and Natural Gas Constraints.” https://www.eia.gov/todayinenergy/detail.php?id=14671.

Lin, Y., J.H. Eto, B.B. Johnson, J.D. Flicker, R.H. Lasseter, H.N. Villegas Pico, et al. 2020. *Research Roadmap on Grid-Forming Inverters*. Golden, CO: National Renewable Energy Laboratory.

Loutan, C., P. Klauer, S. Chowdhury, S. Hall, M. Morjaria, V. Chadliev, N. Milam, C. Milan, and V. Gevorgian. 2017. *Demonstration of Essential Reliability Services by a 300-MW Ssolar Photovoltaic Power Plant*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-67799.

Mai, T., P. Jadun, J. Logan, C. McMillan, M. Muratori, D. Steinberg, L. Vimmerstedt, et al. 2018. *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71500.

Mai, T., M. Mowers, and K. Eurek. 2021. *Competitiveness Metrics for Electricity System Technologies*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72549.

Matevosyan, J., V. Vital, J. O'Sullivan, R. Quint, B. Badrzadeh, T. Prevost, et al. 2019. "Grid-Forming Inverters: Are They the Key for High Renewable Penetration?" *IEEE Power Energy Magazine* 17(6):89–98. https://doi.org/10.1109/MPE.2019.2933072.

Melville, G. 2021. "Companies That Have Set Net Zero Targets." https://carbon.ci/insights/companies-with-net-zero-targets.

Muratori, M., M. Alexander, D. Arent, M. Bazilian, P. Cazzola, E.M. Dede, J. Farrell, et al. 2021. "The Rise of Electric Vehicles—2020 Status and Future Expectations." *Progress in Energy* 3(2):022002. https://doi.org/10.1088/2516-1083/abe0ad.

Murphy, C., T. Mai, Y. Sun, P. Jadun, M. Muratori, B. Nelson, and R. Jones. 2021. *Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72330.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2017. *Enhancing the Resilience of the Nation's Electricity System*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24836.

NASEM. 2021a. *Accelerating Decarbonization in the United States: Technology, Policy, and Societal Dimensions*. Washington, DC: The National Academies Press. https://www.nationalacademies.org/our-work/accelerating-decarbonization-in-the-united-states-technology-policy-and-societal-dimensions.

NASEM. 2021b. *The Future of Electric Power in the United States*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25968.

NEI (Nuclear Energy Insititute). 2018. "History of U.S. Nuclear Plants Responding to Extreme Natural Events." https://www.nei.org/resources/fact-sheets/history-us-nuclear-plants-response-events.

NERC (North American Electric Reliability Corporation). 2007. "Definition of 'Adequate Level of Reliability.' " https://www.nerc.com/docs/pc/Definition-of-ALR-approved-at-Dec-07-OC-PC-mtgs.pdf.

NIST (National Institute of Standards and Technology). 2017. "Transactive Energy: An Overview." www.nist.gov/el/smart-grid-menu/hot-topics/transactive-energy-overview.

NREL (National Renewable Energy Laboratory). 2020. *Flexible Nuclear Energy for Clean Energy Systems, NICE Future.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A50-77088.

Olaniran, O.J., P.E.D. Love, D. Edwards, O.A. Olatunji, and J. Matthews. 2015. "Cost Overruns in Hydrocarbon Megaprojects: A Critical Review and Implications for Research." *Project Management Journal* 46(6):126–138. https://doi.org/10.1002/pmj.21556.

Perez, M., R. Perez, K.R. Rábago, and M. Putnam. 2019. "Overbuilding and Curtailment: The Cost-Effective Enablers of Firm PV Generation." *Solar Energy* 180(March):412–422. https://doi.org/10.1016/j.solener.2018.12.074.

Poudel, B., T. McJunkin, N. Kang, and J. Reilly. 2021. *Small Reactors in Microgrids: Technical Studies Guidance*. INL/EXT-21-64616-Rev000. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1829672.

ReportLinker. 2022. "The Global Microgrid Market Size Is Estimated to Be USD 26.9 Billion in 2022 and Is Projected to Reach USD 63.2 Billion by 2027, at a CAGR of 18.6%." *GlobeNewswire News Room*, July 12, 2022. https://www.globenewswire.com/news-release/2022/07/12/2478322/0/en/The-global-microgrid-market-size-is-estimated-to-be-USD-26-9-billion-in-2022-and-is-projected-to-reach-USD-63-2-billion-by-2027-at-a-CAGR-of-18-6.html.

Ruhnau, O., and S. Qvist 2022. "Storage Requirements in a 100% Renewable Electricity System: Extreme Events and Inter-Annual Variability." *Environmental Research Letters* 17(4):044018.

Saad, L. 2022. "Where U.S. Investors Stand on ESG Investing." *Gallup*, February 23. https://news.gallup.com/poll/389780/investors-stand-esg-investing.aspx.

Sajadi, A., R. W. Kenyon, and B.-M. Hodge. 2022. "Synchronization in Electric Power Networks with Inherent Heterogeneity Up to 100% Inverter-Based Renewable Generation." *Nature Communications* 13(1):2490. https://doi.org/10.1038/s41467-022-30164-3.

Shan, R., A. Abdulla, and M. Li. 2021. "Deleterious Effects of Strategic, Profit-Seeking Energy Storage Operation on Electric Power System Costs." *Applied Energy* 292(June):116833. https://doi.org/10.1016/j.apenergy.2021.116833.

Technavio. 2022. "Microgrid Market Size to Grow by USD 19.5 Billion | Increasing Government Support to Boost Growth | Technavio." *PRNewswire*, June 29, 2022. https://www.prnewswire.com/news-releases/microgrid-market-size-to-grow-by-usd-19-5-billion--increasing-government-support-to-boost-growth--technavio-301576946.html.

Trabish, H. 2019. "De-Energize and DERs: The Tough Options Wildfires Pose for California Utilities." *Utility Dive*, February 20. https://www.utilitydive.com/news/the-hard-choice-californias-wildfires-have-forced-on-its-utilities-and-a/548614.

Vartabedian, R. 2021. "Years of Delays, Billions in Overruns: The Dismal History of Big Infrastructure." *New York Times*, November 28. https://www.nytimes.com/2021/11/28/us/infrastructure-megaprojects.html.

Walton, R. 2022. "U.S. Energy Storage Capacity Tripled in 2021: EIA." *Utility Dive*, July 12. https://www.utilitydive.com/news/energy-storage-capacity-eia-2021-report/627028.

Wilson, C., A. Grubler, N. Bento, S. Healey, S. De Stercke, and C. Zimm. 2020. "Granular Technologies to Accelerate Decarbonization." *Science* 368(6486):36–39. https://doi.org/10.1126/science.aaz8060.

Wongtrakool, B.M., M. Borowske, and F. Vallespir. 2020. *An ESG Perspective on the Automobile Industry*. Western Asset. https://www.westernasset.com/us/en/research/whitepapers/an-esg-perspective-on-the-automotive-industry-2020-02.cfm?srcid=WA_Commentary.

World Nuclear News. 2021. "USA to Hold Inquiry into Cold-Weather Operations." *World Nuclear News*, February 18. https://world-nuclear-news.org/Articles/US-organisations-to-hold-joint-inquiry-into-cold-w.

Ziegler, L., E. Gonzalez, T. Rubert, U. Smolka, and J.J. Melero. 2018. "Lifetime Extension of Onshore Wind Turbines: A Review Covering Germany, Spain, Denmark, and the UK." *Renewable and Sustainable Energy Reviews* 82(February):1261–1271. https://doi.org/10.1016/j.rser.2017.09.100.

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The Economic Challenge

The economic challenge that advanced reactor developers face is daunting. In the current market environment, advanced nuclear reactors will need to be cost-competitive with alternative low-carbon energy technologies. Developers will need to reduce the capital costs needed to deploy these technologies to enable their large-scale market entry and will also need to demonstrate cost and schedule control. As discussed in Chapter 3, nuclear energy is used almost exclusively to generate electricity as its end-product. Current commercial nuclear power plants (NPPs) are economically evaluated as a firm resource, comparable to coal-fired or natural gas-fired technologies. An expansion in the portfolio of market competitors, combined with pricing and regulatory reforms, have impacted the economic viability of nuclear power in some markets over the previous two decades, and will create increased barriers to entry for any advanced nuclear technologies. This chapter summarizes existing and emergent economic and financing challenges for nuclear technologies generally, and advanced nuclear reactors specifically.

> Finding 4-1: The key economic challenge for advanced nuclear reactors is the need to either be cost competitive with other low-carbon energy systems in providing electricity, expand their use to applications beyond the electricity sector, or have an otherwise strong value proposition that encourages investment. Given anticipated market conditions, and the range of low carbon energy technology options, this will require reductions in capital cost.

ADDRESSING THE MARKET CHALLENGE: CAPITAL COSTS, COMPETITIVENESS, AND ENTRY BARRIERS

Despite the challenges of cost competition in electricity markets, which is discussed in Chapter 3, a 2018 study by the Electric Power Research Institute (EPRI) found that advanced nuclear could be economically competitive in some scenarios, identifying several key drivers that may influence future deployments: energy and environmental policies, cost of fuel for alternatives such as natural gas, regional factors such as gas pipelines and existing asset mixes, and capital costs for nuclear investments as evaluated in the context of the costs of other technology alternatives and market variations (EPRI 2018). A 2022 study by Pacific Northwest National Laboratory (PNNL) revalidated the importance of capital costs for nuclear and competing low-carbon technologies in determining the future trajectory of nuclear in the United States and addressed the potential impact of a carbon tax and net-zero emissions policies in leading to growth in nuclear deployment in the future grid (Kim 2022). Beyond market forces, other studies have reflected on opportunities for improved cost control in development, innovation in labor management, and better project governance structures that may help in creating a learning environment where costs actually decline from first-of-a-kind (FOAK) to nth-of-a-kind (NOAK) builds, something not frequently seen in nuclear development (Ingersoll et al. 2020b).

The risks of investing in nuclear power are compounded by the often-significant uncertainties associated with nuclear development costs. The high capital cost and risk of cost growth could impact an investor's willingness to pursue nuclear power when other options are available, even if a plant owner-operator sees utility in incorporating nuclear electricity generation. The uncertainty surrounding these economic risks impacts how investors view nuclear technologies and reducing these risks by lowering up-front costs and demonstrating disciplined cost control could be a key factor in overcoming concerns with a nuclear investment. While the EPRI and PNNL studies highlight the importance of *capital* costs, the entire cost landscape for nuclear development impacts its economic competitiveness and market viability. The PNNL study capital costs are based on the Idaho National Laboratory (INL) *Nuclear Cost Basis Report* (2022)*.* The EPRI data and references are based on input from existing NPPs. The costs of advanced NPPs may be very different from the assumptions in these studies, based on potential differences in design, deployment, operation, and risk drivers. This variation in assumptions leads to significant uncertainty in future nuclear deployment pathways.

Power Plant Cost Drivers and Overcoming the "Sunk Cost" Challenge of Nuclear

Three major cost components in any power plant are capital cost, operating and maintenance costs, and fuel costs. Capital cost is composed of two parts: (1) the "overnight cost," which refers to the cost of building the plant, including equipment, construction materials, site preparation and labor, excluding costs associated with financing and escalation (hence "overnight"); and (2) the cost of capital (interest on funds borrowed to build the plant, financed by either debt or equity). All upfront capital costs are "sunk" costs from the perspective of an investor because they are recoverable only over time from payments from energy production. The cost of capital is affected by the time required to construct the plant and the interest rate on the funds borrowed. In the United States, the cost of capital is dependent on technology, location, and developer; it is determined by how credible investors assess the project to be (i.e., is it a "safe bet" for generating return, and can it attract debt financing?), and a host of other factors including incentives by federal, state, and local authorities.

Once a plant is built, operation and maintenance (O&M) costs depend on the personnel needed and the materials used in operating the facility. The final cost component is the cost of the fuel required to generate energy. Capital costs, along with many components of operating costs, could be considered fixed costs that are incurred whether the plant is in operation or not. O&M costs have a variable component that is affected by personnel changes and materials used.[1] Most fuel costs, by contrast, are variable because they are incurred only when the plant is operating.

Many low-carbon technologies, including nuclear power, are capital-intensive relative to their operating costs. Depending on nuclear plant design, capital cost can account for as much as 80 percent of the lifetime cost of energy from the plant, with the remainder of the cost typically divided between O&M (15 percent) and fuel costs (5 percent) (World Nuclear Association 2022). These percentages can vary for different plants depending on location (owing to differences in site preparation, labor, and permitting), actual plant construction time, and the interest rate on borrowed capital (which itself is a function of construction time). The cost structure for nuclear plants is in direct contrast to that of a natural gas plant, where 80 percent of the total lifetime cost is the fuel cost (EPRI 2018).

Because the dominant cost component for nuclear technology is the capital cost, it is instructive to provide a typical cost breakdown of that cost component. Following the classification approach used by Black and Veatch in 2012, a 2018 MIT report found that for current light water reactor (LWR) plant construction projects (AP1000 in the United States, EPR in Europe, AP1400 in UAE), a small fraction of the overnight capital cost is owing to the nuclear island equipment (10–20 percent) and even less for the turbine-generator equipment (5–10 percent) (Buongiorno et al. 2018). As shown in Figure 4-1, most of the overnight cost was taken up by engineering, procurement, and construction (EPC) costs (10–20 percent), the cost of civil work (40–50 percent), and owner's costs (10 percent).[2] In its projections for

[1] Other O&M costs include water usage, discharge treatment, chemicals, and consumables (EIA 2020).

[2] Engineering procurement and construction costs are related to indirect engineering, quality assurance (QA), and supervisory costs. Cost of civil works includes costs to prepare the site, including excavations and foundations,

market viability, the same MIT study independently estimated NOAK overnight capital costs for advanced reactor designs that were between $4,600 and $5,400 per kWe. It is noteworthy that the overnight cost estimates provided by the advanced reactor vendors to the committee were far lower (by ~50 percent). The capital cost mix may change if advanced reactors realize their goal of development using a manufacturing model,[3] but it is still unclear if this would reduce the overall cost burden or simply shift the costs to development of a manufacturing support infrastructure. An in-depth discussion on EPC and civil works challenges is presented in Chapter 6, including a discussion of reasons for cost overruns and potential differences in cost outcome depending on the size and design of a reactor, and the manufacturing approach.

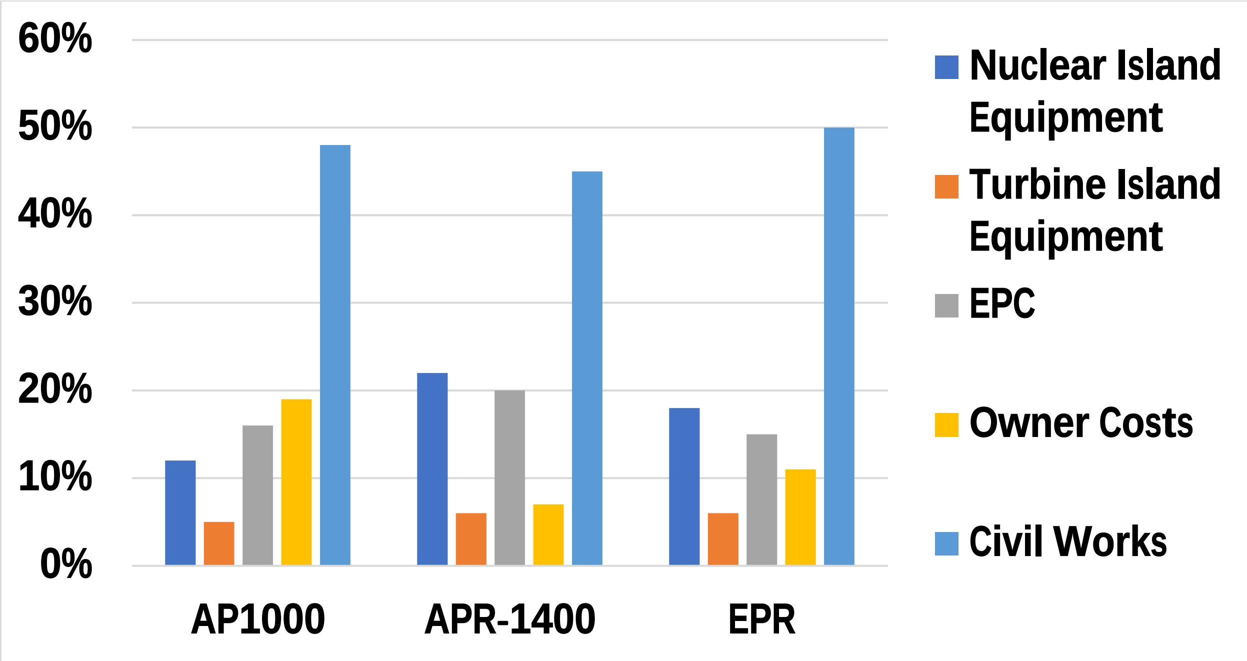

FIGURE 4-1 Overnight capital cost breakdown for advanced light water reactors.
SOURCE: Committee generated based on data from J. Buongiorno, M. Corradini, J. Parsons, et al., 2018, "The Future of Nuclear Energy in a Carbon-Constrained World," Massachusetts Institute of Technology Energy Initiative, Cambridge, MA, https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf.

A more recent study of cost drivers for nuclear-specific development evaluated multiple nuclear projects to determine the dominant cost driver categories—that is, those that had the greatest influence on cost growth/overrun (Ingersoll et al. 2020b). A notable aspect of the analysis was a comparison of U.S. and European construction experience with that in the rest of the world (ROW). The evaluation highlighted the role of different construction practices, raw material costs, labor market costs, regulatory burdens, and financing structures.[4] Highlighted here are several issues not tied to location, which should

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the ultimate heat sink (e.g., cooling towers), other equipment, and the installation of plant components. Owner's cost includes fees, permits, taxes, owner's engineering costs, and costs for spare parts and commissioning.

[3] The distribution of costs will also be specific to reactor design, and some traditional LWR cost categories may be inapplicable to new designs. See Ingersoll (2020b) for a discussion of potential cost differences. Additional cost analysis will be required as designs reach technical maturity.

[4] ROW funding is often a significant factor in controlling overall costs given that financing costs during the build can escalate if there are schedule delays.

be addressed by *any* new nuclear developer to help control the costs of nuclear power in future developments. Specifically, successful programs have ensured that there is:

- A completed design prior to construction;
- A fully detailed development schedule that incorporates adequate quality assurance oversight;
- Adherence to a detailed build schedule;
- Sustained learning effects from repetitive builds of the same design;
- Preferential tax policies and cheaper financing.

The first four items relate to the management of development projects and are addressed along with other project management issues in Chapter 6. Notably, the passage of the Inflation Reduction Act (IRA) of 2022 recognizes nuclear as a low-carbon energy source eliminating uneven treatment of this technology compared to other low carbon technologies. Tax policy and finance mechanisms are addressed later in this chapter.

> Finding 4-2: Nuclear developers face higher financing costs, and thus a greater sunk cost burden, than developers of other energy technologies. These higher costs result from (1) uncertain development and build times and (2) limited financing options and high interest rates that increase the finance burden, partly a result of a poor track record and consistent cost overruns in past construction.

UNIQUE ADVANCED REACTOR COST DRIVERS

Beyond the typical capital cost drivers, there are also unique cost drivers that advanced reactor developers will need to address, including a potentially more complex fuel cycle for some designs. Given the lack of reliable cost data on development of a fuel production facility, it is treated qualitatively rather than quantitatively in this report. The absence of a common fuel type among the competing advanced reactor designs means that multiple fuel supply chains will have to be developed for fuel fabrication at the required enrichment. Additionally, before a fuel supply vendor would choose to develop a facility, there must be sufficient demand (absent a continuing U.S. government commitment to develop and maintain a strategic capability and supply) to justify the development of new fabrication capabilities. This is further complicated by the extended fuel cycles (longer time between refueling) envisioned for several advanced reactors, which may result in intermittent demand absent an extended fleet development effort. If enough reactors of similar design are ordered over time, demand can be levelized despite the long fuel cycles for each reactor. However, it may be difficult to justify significant capital investment for supply chains that do not have regular demand. This may be particularly true for fuel production facilities that support multiple reactor types and that do not allow the standardization of processes or production cycles. Longer core lifetimes envisioned by the vendors can potentially offset a portion of the high cost of developing a new fuel form, but there is limited data to establish that higher fuel burnup will offset the added cost drivers. Additional analysis is needed to clearly demonstrate that the costs of developing a new fuel fabrication facility (or backfitting an existing facility) and the costs of higher assay fuels will be sufficiently mitigated by the longer core lifetimes postulated and other strategic planning efforts, such as staggered refueling schedules.

Multiple reactor designs also anticipate the use of high-assay low-enrichment uranium (HALEU). The supply chain for this more highly enriched fuel has additional costs associated with controls for special nuclear material of moderate strategic significance (NRC Category II). Until 2021, the absence of a reliable domestic HALEU supply chain meant that Russia was sometimes referred to as a potential supplier of necessity for HALEU. The 2022 Russian invasion of Ukraine has likely made this a non-viable pathway for the foreseeable future. Even when the war ends and if relations with Russia thaw, the energy security and geopolitical implications associated with this pathway will remain.

The implementation of a once-through fuel cycle would simplify cost assumptions for FOAK development and reduce regulatory risk, because costs for wet and dry storage are relatively well established. However, this eliminates one of the stated advantages of some advanced nuclear reactors—to reduce existing or future stockpiles of nuclear waste. If interim fuel storage is required for advanced reactor spent fuel, new storage casks for more unique fuel forms, and new facilities for processing novel fuel forms may be needed, both of which incur costs. However, a passively safe cask design would result in minimal operating costs and risk. Yet, successful widespread deployment of small reactors at a level that would contribute to greenhouse gas mitigation would require hundreds—potentially thousands—of reactors deployed at both current and new nuclear sites. Without developing centralized storage sites, a repository, or a fuel reprocessing capability, the waste management challenge might become even more urgent in a world dominated by small, advanced nuclear reactors. While there has been limited business or political interest in developing consolidated storage sites in the United States, two license applications have been submitted for interim storage facilities in Texas and New Mexico (NRC 2021a,b). These sites face political opposition, and waste disposal issues for advanced reactors face continued uncertainty. A recent National Academies report discusses this issue in great depth (NASEM 2022). Additional discussion on regulatory and societal challenges associated with storage facilities is available in Chapters 7 and 8.

The fuel cycle is not the only area where new designs may face supply chain challenges. For other critical specialized components (pumps, valves, heat pipes, etc.), design differences limit economies of scale that could reduce capital costs. As a result, government financial support may be required to ensure that supply chains are developed and maintained if a diverse advanced reactor ecosystem develops. Government support will likely be necessary at the early stage to help catalyze development of particular components, because private capital may be hesitant to invest before a vendor has clearly demonstrated a market for its design. There will, of course, be risk in this government support in that until there is growth in demand, there will be limited development of a supporting supply chain, and until there is a more robust supply chain with learning, costs will not come down to support cost reductions from FOAK to NOAK—a classic "chicken and egg" conundrum. Regardless, to demonstrate cost reductions, vendors will need stable supply chain support—which makes government funding the likely bridge to address a "supply chain valley of death." Down-selecting to a more limited number of designs would reduce the supply-chain cost burden and focus government spending—this approach is discussed later in the chapter.

> Finding 4-3: Commercialization of multiple designs would logically necessitate the development of a variety of supply chains. For example, there are multiple fuel types proposed for the competing advanced reactor designs. Extended operating cycles with fewer refueling outages may affect demand stability for nuclear fuel. Thus, fuel fabrication may exacerbate the cost challenges for nuclear power.

OTHER DRIVERS OF PERCEIVED UTILITY IN ENERGY MARKETS

Many other factors could influence the choice between generating options in a competitive market. The fundamental question is the "willingness to pay" for nuclear generation. In most electricity markets today, the primary comparative attribute used by energy service providers is levelized cost and levelized avoided cost when considering alternative technologies. However, as the energy transition unfolds and the supply, demand, regulatory, pricing, and technical pictures change, the various other attributes that advanced nuclear could provide may be valued sufficiently that a customer would be willing to pay a premium for this technology.

In some cases, an electrical generation company expanding its resource portfolio might determine that there is utility in having a balance of generation resources to ensure greater flexibility and reliability. This would differ substantially across locations and regulatory environments, rendering the estimation of a "new nuclear market" spatially dependent and uncertain (discussed further in Chapter 3). For example, where there is more limited renewable energy (RE) resource or greater restrictions on natural gas supply, there may be a more credible market opportunity for nuclear developers. While this scenario could tip the balance toward nuclear, the most likely outcome is decidedly unclear. But resource availability and cost are not the only factors that influence investment.

In addition to the pure economic factors, other decision criteria should be considered when selecting among energy generation technologies, including some that are not easily monetized. Within the field of behavioral economics, there has been significant consideration of the difference between a pure economic preference assessment, which is generally tied to evaluations and comparison of economic value, and a broader suite of considerations that affect choices, in which equity, safety, risk, public acceptability, and other societal impacts all play a role (EIA 2014).

OTHER ECONOMIC CONSIDERATIONS

Overall grid costs and cost avoidance are additional considerations in determining the viability of nuclear as a low-carbon resource. A 2022 study by Vibrant Clean Energy (sponsored by the Nuclear Energy Institute) indicated that constrained deployment of nuclear in decarbonization scenarios led to as much as $346 billion in additional development costs to reach comparable levels of grid decarbonization by 2050. While this study makes untested assumptions about nuclear NOAK costs, there is still a valid concern tied to overall system cost. If low-carbon sources such as nuclear are discounted before they are fully evaluated, higher overall electricity system costs are possible as much lower capacity factor solutions are deployed to meet growing electricity demand (Clack 2022). As noted in Chapter 3, an options approach that maintains flexibility in technology choice for as long as possible may be better in ensuring that this technology transition does not lead to costly dead ends.

To maintain flexibility, there may be value in the current approach by DOE to support smaller scale nuclear alternatives. Prior studies of nuclear construction costs have indicated that diseconomies of scale exist with nuclear power development and deployment based on the association between increases in plant size and increases in cost on a $/mWe basis (Talabi and Fischbeck 2013). Economic flexibility is often greater when the scale of the economic risk is lower for any individual technology of choice. Smaller scale yields opportunities for factory manufacture and assembly that could substantially mitigate many of the identified cost drivers in traditional construction, as well as enabling staged deployment and more controlled expansion, which may lower investment and deployment execution risk. Smaller scale may also better enable penetration into microgrid and alternative industrial process heat markets and provide a path to larger order books that may yield economy of scale through deployment, as well as a beneficial learning curve.

> Finding 4-4: Diseconomies of scale exist in certain nuclear power development and deployment scenarios. The diseconomies of scale may be owing to increased complexity and addition of systems associated with increased plant size, as well as the need for robust supply chains to support additional complexity and size.

> **Recommendation 4-1: The Department of Energy should continue to support developers in their efforts to design smaller plants and microreactors. This may be an early and low-risk path for nuclear deployments in certain selected applications where reduced scale may enable better control of cost and schedule overruns, potentially creating demand-pull, a larger number of orders, and greater potential for rapid learning.**

In summary, the key economic challenge for advanced nuclear reactors is reduction in the up-front capital costs (i.e., sunk costs) needed to develop and deploy these technologies so that they are cost competitive with other low-carbon energy systems. Achieving cost-competitiveness would enable advanced reactors to enter the market and attract enough private investment to be deployed at scale, whether the primary goal is to provide electricity or to support industrial processes. As with most energy technologies, federal government support will be required in many phases of the research, development, and demonstration process. The next section addresses frameworks for private–public cooperation that will almost certainly be necessary to clear technical and commercialization barriers to entry for advanced nuclear. This economic challenge also translates into a financial challenge for advanced reactors: there will be limits to acquiring the necessary funds for widespread deployment of advanced reactors. The financing challenge and financing avenues are addressed after a discussion of government's role in demonstration.

STRUCTURE AND PARAMETERS FOR PUBLIC–PRIVATE PARTNERSHIPS TO PURSUE DEMONSTRATIONS

Today, private industry is moving forward with several advanced nuclear technologies. Building on past work that began with substantial federal funding, these advanced nuclear reactor developers are aiming to produce electricity as well as other energy products beyond electricity that can potentially address a broader set of energy services. The readiness of different nuclear concepts varies, with some developers aiming for demonstration in this decade, while others target demonstrations early in the next decade.

As described in Chapter 2, each new design has different levels of technology and system readiness. Federal and state governments have thus expanded their efforts to support technology development, and many private developers have taken a pragmatic approach that recognizes their diverse development needs and have shown a willingness to incorporate aspects of private-public partnership, especially in completion of higher-risk R&D. Such a framework will be necessary to result in successful demonstration of first-of-a-kind advanced reactors.

An American Nuclear Society Task Force proposed a set of development phases for private-public partnerships that would involve teams of industry, national laboratories, and universities (ANS Task Force 2021). The Task Force report outlined the necessary phases of a technical approach that would support the ongoing advancement of nuclear energy concepts from the required applied research, the development of advanced concepts, and then deployment of these reactor concepts. This approach would (1) maintain national R&D infrastructure capabilities for these teams; (2) enable teams to innovate new reactor concepts; (3) develop promising concepts by industry for demonstration that meet technical milestones; (4) demonstrate a few select concepts; and (5) commercialize successful demonstrations for deployment.[5] Such activities could be developed at a faster pace to get maximum value from public as well as private investments in this decade.

To facilitate such a development structure, development teams can employ DOE's recently established National Reactor Innovation Center (NRIC) and the Gateway for Acceleration of Innovation in Nuclear (GAIN) programs (see Box 4-1). These programs were specifically established to connect private industry teams to federal nuclear R&D experimental facilities and analysis capabilities. These infrastructure programs support activities that would receive federal financing, such as the newly created Advanced Reactor Demonstration Program (ARDP), which is a private–public partnership.

BOX 4-1
DOE Programs to Facilitate Nuclear Industry and Government Coordination

[5] Note that some of these elements may not be needed for mature advanced reactor concepts. Also, the ANS description of the phases has been modified by separating the demonstration phase from the commercialization phase. Demonstration would likely involve direct financial involvement by the government in partnership with a vendor and owner-operator. Commercialization would likely involve private investment with the government providing more indirect financial incentives.

GAIN: Gateway for Accelerated Innovation in Nuclear

While many innovative ideas exist for advanced nuclear systems, the R&D needed to bring these concepts to a commercial readiness level can be substantial. The DOE GAIN initiative provides the nuclear industry with access to DOE technical, regulatory, and financial support necessary to move innovative nuclear energy technologies toward development. GAIN facilitates access to state-of-the-art DOE R&D infrastructure available to industry for faster and more cost-effective development of innovative nuclear technologies to commercial readiness. Some of the capabilities supported through competitive NE vouchers administered by GAIN include

- Experimental capabilities with primary emphasis on nuclear and radiological facilities, but also other testing capabilities (e.g., thermal-hydraulic loops, control systems testing, etc.);
- Computational capabilities along with state-of-the-art modeling and simulation tools;
- Information and data through a knowledge and validation center; and
- Access to legacy documents that could help industry shorten development and decrease cost.

NRIC: National Reactor Innovation Center

NRIC, a new program funded by DOE beginning in 2019, facilitates the development and demonstration of advanced reactor systems through a suite of services and capabilities. NRIC includes an interdisciplinary team that can leverage government resources to meet private industry needs. Support from NRIC could include assistance in navigating permitting and regulatory pathways from start to finish, as well as help with contracting and local stakeholder engagement for siting. NRIC efforts are unique in preparing for reactor demonstrations, and include

- Demonstration of Microreactor Experiments (DOME) Test Bed site capable of hosting operational experimental and test nuclear reactor concepts that produce less than 20 MW thermal power suitable for DOE Authorization;
- Laboratory for Operating and Testing in the United States (LOTUS) Test Bed capable of hosting operational test and experimental nuclear reactor concepts that produce less than 500 kW thermal power suitable for DOE Authorization;
- Evaluation of Demonstration Site Alternatives; and
- Funding for collaborative R&D efforts between industry and the national laboratories that directly enable future demonstrations of advanced reactors.

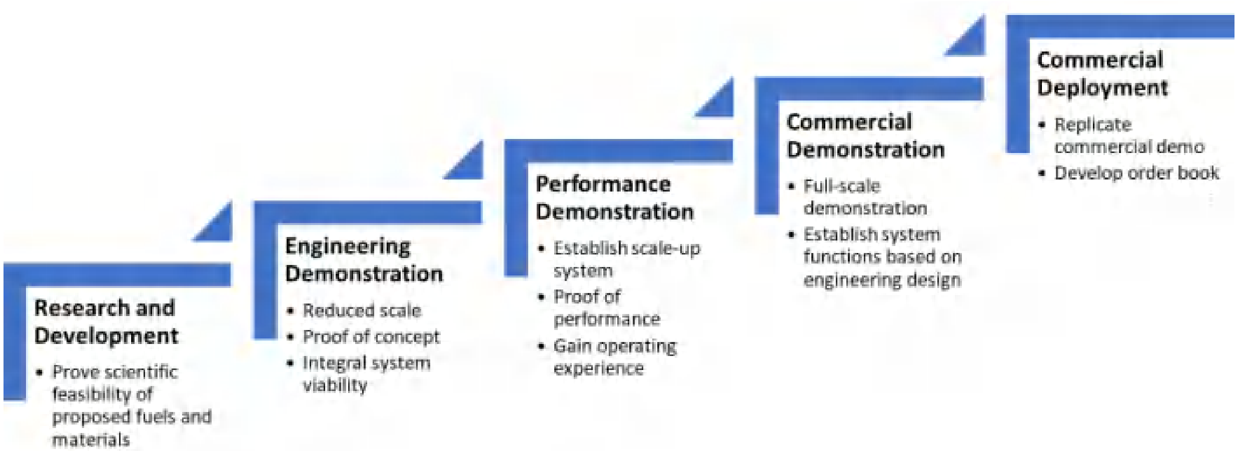

FIGURE 4-2 Historical paradigm for commercializing nuclear power technologies.
SOURCE: D. Petti, R. Hill, J. Gehin, et al. 2017, “A Summary of the Department of Energy’s Advanced Demonstration and Test Reaction Options Study,” *Nuclear Technology* 199:111–128, https://doi.org/10.1080/00295450.2017.1336029.

Given this overall structure, certain key elements could be part of a private–public partnership, as suggested by Petti et al. (2017) and EPRI (2017). These reports suggest similar cost sharing concepts and financing approaches that begin with government support of R&D facilities, co-funding of R&D activities that lead to a reactor concept via private–public partnerships, and eventually industry-funded commercialization with government financial incentives. Similar approaches have been used by NASA and Space-X (Box 4-2). Figure 4-2 provides a conceptual picture of these elements, and Petti et al. (2017) note that some of these development stages may not be needed for more mature reactor concepts.

Not all advanced reactor concepts have followed this development pathway. NuScale leveraged the substantial collective experience with LWR technology to move directly to a combined performance demonstration and commercial offering. Given that a plant site may house several modules, the first nuclear power module is planned to demonstrate acceptable performance, followed by installation of the other modules as part of the commercial plant. For the high-temperature gas-cooled reactor and the sodium fast reactor, a few prior engineering demonstrations have served as proofs-of-concept. The current design concepts are relatively mature, so developers (X-Energy and TerraPower) are aiming to adopt a similar model that combines performance and commercial demonstration. In contrast, for the molten salt concepts that are not as mature (e.g., Kairos), an engineering demonstration is part of the development pathway for the vendor to reach commercial demonstration and potential deployment.

BOX 4-2
Creative Approaches by NASA to Enable the Creation of SpaceX as a Commercial Leader in Commercial Global Launch Services

Between 2010 and 2017, the United States went from having no commercial launch vehicles for space applications (with Russia being the international leader) to having nearly 50 percent of the international market. This shift occurred as NASA transitioned its programs to enable the creation and growth of SpaceX. Such a transition was possible because NASA deployed a new model for working with the private sector that provided commercial incentives for technology development and private finance.[a]

Both technology improvement as well as large-scale financing are current challenges for developing a new generation of advanced reactors. Similar to NASA's transition, DOE and other agencies supporting international development need to transition their support for nuclear energy from a system that has traditionally research-based to one that has balanced elements of research and incentives to commercialization. The programmatic themes used by NASA to enable their transition that could be adopted by DOE for advanced nuclear energy include

- Milestone-based, fixed-price payments that limit government responsibility for cost overruns compared with traditional "cost-plus" contracts;
- Cost sharing with private investors;
- Use of "other transactions" authority from the 1958 Space Act that enabled agreements that were neither procurements nor grants, and were not subject to the complete Federal Acquisition Regulations (FAR);
- Conservative treatment of proprietary information, leaving full rights with the private companies;
- Consultation with a venture capitalist, who had prior government experience and who assisted in the design and implementation of the program; and
- NASA and the federal government also served as early customers for SpaceX, guaranteeing an early revenue stream that quickly expanded to include private-sector customers from around the world.

The NASA program showed discipline in executing the milestones-based approach. A private company, Rocketplane-Kistler, did not meet milestones, was not offered further support, and the public–private partnership was terminated.

[a] M. Bowen, 2019, *Enabling Nuclear Innovation in Search of a SpaceX for Nuclear Energy: A Report by the Nuclear Innovation Alliance.*

DOE is playing a key role across the advanced reactor development landscape by funding multiple designs for demonstration, risk reduction, and further research and development. This federal government support will be crucial in mitigating technical challenges that lead to risk in development and could affect the sunk cost burden. For example, these government programs involve private-public partnerships that:

- Assist the developer of mature reactor concepts in completing the detailed design and help engage the regulator to review the design and its ability to meet safety criteria.
- Reduce the risk of maturing reactor concepts in demonstrating the satisfactory performance of innovative safety systems.
- Provide R&D funding for less mature concepts to develop needed materials and fuels.

The following section summarizes these advanced reactor program efforts and Appendix D describes in detail the breadth of these DOE programs.

ADVANCED REACTOR DEMONSTRATION PROGRAM—PATH FORWARD

The Advanced Reactor Demonstration Program (ARDP)[6] formally started in fiscal year (FY) 2020 and supports advanced reactor development through a collection of legacy R&D programs within DOE and through this congressionally authorized demonstration program. ARDP provides funding for two reactor demonstrations at higher technology readiness levels (TRLs)[7] and risk reduction for reactors at lower TRLs. As of December 2021, DOE established the Office of Clean Energy Demonstrations (OCED), which now manages the ARDP's two reactor demonstration projects.

The overall DOE program has elements in addition to ARDP. The combined portfolio includes

- University-led research with industry and national laboratory teams;
- Industry-led research through targeted Funding Opportunity Announcements;
- Laboratory-led advanced SMR program for early-stage, crosscutting engineering technologies;
- Laboratory-led advanced reactor technology program for long-term innovative technologies; and
- ARPA-E independent programs in support of nuclear energy.

The details of the current DOE programs are discussed in Appendix D.

It is important for DOE to ensure that its investments will constitute a sustainable, innovative holistic program, not just a set of loosely coordinated individual programs. Since the initiation of ARDP

[6] The ARDP program was funded in FY 2021 appropriations at $80 million for each demonstration project, $40 million for risk reduction efforts and $15 million for regulatory development. The FY 2022 President's Budget increased funding for the two selected demonstration projects to $109 million and $136 million, respectively, and increased risk reduction funding to $50 million. The federal demonstration funding is a 50 percent match for the private investments by the two industrial teams for the Natrium and X-Energy reactor concepts.

[7] First developed by NASA in the 1980s, the Technology Readiness Level (TRL) is a type of measurement system used to assess the maturity level of a particular technology. The scale ranges from 1 (basic principles observed) through 9 (total technological system used successfully in project operations) (NASA 2021).

as a separate program in 2020, there appears to be a need to assess and organize these multiple programs to minimize potential duplication of program goals (unless warranted for specific research objectives) and to align overall research and development as well as demonstration efforts. However, some of the necessary organizational support structures have come to exist through NRIC and GAIN, which are described in Box 4-1.

The overall structure of ARDP partnerships needs to have a comprehensive set of development phases for these private-public partnerships. A coherent progression of technology development, kept on target by assessments at key milestones with established metrics, could be organized to produce reactor concepts ready for deployment and ensure innovations in efficiency and design.

For the ARDP demonstrations to be successfully completed by the end of this decade,[8] the program needs to receive full funding for these first two demonstration projects. The Bipartisan Infrastructure Bill, passed in Congress in November 2021, funded the ARDP projects only through FY 2025 (Nuclear News 2021; see Appendix D). As part of the ARDP, an additional eight reactor concepts are supported by DOE for risk reduction and early-stage design. Realistically, not all these reactor concepts will see their way to eventual demonstration. Rather, DOE should plan for a down-selection to a few concepts that can proceed. The purpose of including agreed-upon milestones is to explicitly establish the criteria for the down selection.

Plant owner-operators, industry developers, and DOE as well as its laboratories need to develop a coordinated plan to support necessary development efforts for those selected designs. While initial efforts reflect a desire to broadly support multiple promising concepts, the ARDP ultimately needs a well-vetted strategic technology development plan, with performance milestones that are closely coupled with the long-range funding strategy. This plan would factor in issues such as ongoing design progress and adherence to cost and schedule and would dictate assessment against a consciously chosen set of competitive criteria to allow recurring review and support for those concepts that continue to meet cost targets, regulatory milestones, and technology development goals. As technology development progresses, it may be necessary to consider a staggered approach to demonstrations to ensure affordability for the overall program (e.g., two demonstrations through the planned 2027 timetable and two more chosen from risk-reduction potential candidates). It is in the long-term interest of DOE to ensure multiple demonstrations are completed given the uncertainty in long-term operability or affordability of any single design. Thus, it is critical that DOE remain supportive of continuing the ARDP effort, including technology risk reduction for lower TRL designs, even if one of the more mature concepts shows promise in initial demonstration. That said, it is also important that DOE adhere to a milestone approach that includes “off-ramps” for technologies that do not meet specified goals across cost, schedule, and performance.

As discussed in more detail in Appendix C, past DOE support for commercialization programs such as the NP2010 Program successfully led to commercial opportunities for more advanced light water reactor designs. Despite the success of that program in generating utility interest in deploying these new designs, one of the resulting development efforts—the V.C. Summer project in South Carolina—was ultimately cancelled after billions of dollars were invested, and the second project at Vogtle in Georgia has suffered extensive schedule delays and cost overruns (see Chapter 6 for a discussion).[9] While some assessment of these development programs has been completed, examining these efforts in the context of execution of the ARDP may be beneficial in order to ensure the lessons learned from the Vogtle and V.C. Summer projects are factored in. Specifically, the reexamination needs to assess issues associated with project management and civil engineering, which to date do not seem to be a prominent aspect of the ARDP, but which may have a greater bearing on ultimate commercial viability than demonstration of the fundamental nuclear technologies. The issue of project management and the importance of lessons learned is discussed in more detail in Chapter 6.

[8] Current ARDP plans indicate a completion of these projects by 2027. This seems optimistic; the early 2030s is more realistic.

[9] Both AP1000 projects were fixed-price contracts.

Given DOE's efforts to demonstrate new reactors and the uncertainty that exists, vendors should aim for costs that are close to $4000–$5000/kWe overnight (see Chapter 3). This is also supported by past studies that suggest the need to reach similar NOAK overnight costs (EPRI 2018; Buongiorno et al. 2018). While the committee did not receive detailed cost estimates from vendors, most acknowledged a need to meet likely market thresholds of <$5000/kWe. Some indicated that they anticipated reaching less than ~$3000/kWe over time for a NOAK plant, suggesting that with a sufficiently large order book, learning would drive costs lower (Lovering et al. 2020). These claims were not backed by a clear assessment of how large that order book would need to be, any evidence of supply chain readiness, estimates of cost of unique fuel designs (including HALEU), or cost factors anticipated in developing a manufacturing infrastructure. Importantly, most vendors pointed to a manufacturing approach as a necessary precursor to achieving their cost reduction goals. The committee notes that the average cost to reach readiness level for demonstration for most nuclear technologies has exceeded $1 billion for each design; however, this could be consistent with a slower, structured approach to a broad future technology portfolio (Ford 2019). Prototype and demonstration plant costs have varied based on scale, but the anticipated government cost share for the ARDP effort is $3.2 billion, which will be matched by the industry participants. Given the lower plant output for the Natrium (345 mWe) and X-Energy Xe-100 (four power modules, each at 80 mWe) designs, the implied demonstration cost is likely >$10,000/kWe for these initial plants, which provides an indication of the cost reductions required to reach market competitive prices.[10]

> Finding 4-5: Past studies suggest that for advanced reactors to achieve a strong market demand signal, it is likely that they will need to reach overnight capital costs in the range of ~$4000–$5000/kWe. While final costs for planned Advanced Reactor Demonstration Program (ARDP) plants are still quite uncertain, the level of government funding and vendor matching contributions (for the first-of-a-kind [FOAK] demonstrations) implies a cost level of approximately 2–2.5 times the $4000–$5000/kWe cost threshold. Significant and rapid learning and cost reductions will be necessary when moving from FOAK to nth-of-a-kind (NOAK) cost levels.

OTHER DOE EFFORTS TO SUPPORT TECHNICAL DEVELOPMENT

DOE has made other efforts to further the research and development of new reactor designs. While covered in more detail in Appendix D, some topics merit a mention here given their potential impact in overall viability of the DOE portfolio.

In the area of support for small modular reactor development, DOE continues to provide funding and material support for NuScale Power. In 2013, the company was selected as the winner of the DOE competitively bid, $226 million, 5-year, financial assistance award to develop this SMR LWR technology. In 2015, DOE awarded a $16.6 million to NuScale Power for the preparation of a combined Construction and Operating License Application (COLA) with its first customer, Utah Associated Municipal Power Systems' (UAMPS) for the Carbon Free Power Project (CFPP). UAMPS plans to site a NuScale reference plant in Idaho that is expected to be operational by the end of this decade.

DOE also has ongoing efforts to provide national R&D test-beds in support of advanced reactor R&D. These test-beds involve cutting-edge experimental capabilities, computational capabilities, and databases, and staffing those activities with qualified people. Current experimental test beds include the Advanced Test Reactor (ATR), the Transient Reactor Test Facility (TREAT), and the High Flux Isotope Reactor (HFIR), and require appropriate federal and industry support to maintain their capabilities. The

[10] Natrium, a 345 MWe reactor, has total funding of $4 billion (e.g., $11,600/kWe) while X-Energy, a 320 MWe design, has funding of $2.464 billion (e.g., ~$7700/kWe; combined DOE and company match). Source: GAO-22-105394 of September 2022 "DOE Should Institutionalize Oversight Plans for Demonstrations of New Reactor Types."

other program that has generated significant funding and development is the Versatile Test Reactor. However, ongoing Congressional budget deliberations have placed the VTR at risk, highlighting the challenge that DOE faces in attempting to support such a breadth of programs within the DOE-NE budget.

Last, two major programs in nuclear energy are currently funded through a sub-office within DOE—the Advanced Research Projects Agency–Energy (ARPA-E). The Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration (MEITNER) program was created to develop innovative technologies that can enable advanced reactor designs to achieve lower cost and safer operation. These enabling technologies could establish the basis for a modern, domestic supply chain supporting nuclear technology. The MEITNER program began in summer of 2018 and made 10 awards totaling $24 million. The Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA) program seeks to develop digital twin technology for advanced nuclear reactors and transform operations and maintenance (O&M) systems for advanced nuclear plants (explained further in Chapter 6). The GEMINA program began in summer of 2019 and made 10 awards totaling $27 million. Given the increasing funding being allocated to advanced reactor research by ARPA-E, it will be vital that the goals of this office remain well aligned with the future vision of the broader DOE-NE funded efforts.

While there are many efforts under way to support technical development, the current DOE portfolio is not structured to continuously move ideas from basic discovery to deployment and, as recently detailed by the Government Accountability Office, has not incorporated independent reviews of ARDP project performance nor demonstrated the ability to make funding decisions based on accomplishment of critical development milestones.[11]

Finding 4-6: The Department of Energy (DOE), Office of Nuclear Energy, and Office of Clean Energy Demonstration portfolios support national infrastructure, databases, and human resources; basic discovery research; concept development and improvement; and support for demonstrations. As a means of reducing risk against an uncertain future, the portfolio entertains a diversity of approaches and designs. At the same time, strong evaluation criteria are warranted for deciding on programmatic elements subject to careful consideration of realistic budget constraints. The current DOE portfolio is not structured to continuously move ideas from basic discovery to deployment and has not incorporated independent reviews of Advanced Reactor Demonstration Program (ARDP) project performance nor demonstrated the ability to make funding decisions based on accomplishment of critical development milestones. There is a risk that future funding instability and lack of rigorous oversight may result in a failure to achieve the program goal of demonstrating multiple nuclear technologies that can be commercialized.

Recommendation 4-2: The nuclear industry and the Department of Energy's Office of Nuclear Energy should fully develop a structured, ongoing program to ensure the best performing technologies move rapidly to and through demonstration as measured by technical (testing, reliability), financial (cost, schedule), regulatory, and social acceptance milestones. Concepts that do not meet their milestones in the ordinary course should no longer receive support and newer concepts should be allowed to enter the program in their place.

Recommendation 4-3: Congress and the Department of Energy (DOE) should maintain the Advanced Reactor Demonstration Program (ARDP) concept. DOE should develop a coordinated plan among owner/operators, industry vendors, and the DOE laboratories that supports needed development efforts. The ARDP plan needs to include long-range funding

[11] GAO-22-105394 of September 2022, "DOE Should Institutionalize Oversight Plans for Demonstrations of New Reactor Types."

linked to staged milestones; ongoing design, cost, and schedule reviews; and siting and community acceptance reviews. This plan will help DOE downselect among concepts for continued support toward demonstration. A modification in the demonstration schedule that takes a phased (versus concurrent) approach to reactor demonstration may be required. For example, funding would be continued for the first two demonstrations under the ARDP. A second round of demonstrations of designs expected to mature from the current ARDP Risk Reduction for Future Demonstrations award recipients could be funded for demonstration under an "ARDP 2.0" starting thereafter and going into the future.

ADVANCED REACTOR COMMERCIALIZATION PROGRAM

The preceding section described government efforts to support technical development of advanced reactor technologies through R&D support programs. Even if programs such as ARDP are successful in demonstrating the possible viability of advanced reactors, the overall aim of the effort would not be achieved unless the barriers to wide scale deployment are overcome.

It is appropriate in this context to consider the financial challenge in terms of the overall commitment to aggressive climate goals. Decarbonizing the global energy system is estimated to require world capital investments on physical assets of about $275 trillion through 2050 (Krishnan et al. 2022). Electric infrastructure alone is estimated to require investment on the order $800 billion per year for much the period from 2030 to 2050 (IEA 2021b). Achieving net zero in the United States is estimated to require at least at least $2.5 trillion in additional capital investment (relative to business as usual) in energy supply, industry, buildings, and vehicles over the next decade (Larson 2021). While these estimates are very uncertain, they reflect the likelihood that an immense amount of capital will be required. In the United States and similar economies, a large share of the financing will have to be marshalled by private investors through traditional equity and debt markets. Funding on the scale that is needed for widespread commercialization is simply not available in the venture capital and private equity markets.

To attract adequate funding from the standard public markets, an investment must present sufficiently low risk that large-scale financing can compete with other "ordinary" investments. As a result, an investor's perceptions of risk will greatly influence the evolution of the energy system. A technology option might appear to generate a lower-cost electricity portfolio to an analyst who is building a large-scale optimization model, but prudent investors will consider the credibility of a technology solution, the magnitude of the risks, and the incentives that are offered to support it. Understanding how capital is likely to flow to support different options—including advanced nuclear power—requires listening to investors and their assessments of credibility.

The credibility of a technology option is a function of a hard-nosed assessment of costs and markets, the historical deployment record, technological readiness, and the magnitude and impacts of uncertainties. In this respect, advanced technologies are, by definition, riskier bets than established ones. In assessing the credibility of an emerging technology option, investors often consider the historical record. How successful have the developers been in commercializing (and selling) past technologies? How much of their own equity have they invested in the new technology, and are these investments bearing fruit? Are there risks that could constrain deployment even if the technology operates within its expected performance envelope, and is the developer serious in its effort to mitigate those risks? And who will bear completion risk, particularly for FOAK units?

In this respect, investments in capital-intensive energy infrastructure, such as nuclear power, are at a disadvantage. Across countries and sectors, there is a poor record of cost and schedule control with most such megaprojects (Flyvbjerg 2014; Garemo 2015; Olaniran et al. 2015; Callegari et al. 2018; Vartabedian 2021). Concerns are likely to be given special prominence in connection with nuclear projects given the experience with recent construction projects. in the United States and Europe. The demands on an organization—both hard, in the form of resources and manpower, and soft, in the form of managerial skills and a high reliability mind-set—are high. This matter is covered further in Chapter 6.

To compete on the technical merits with other electricity generation options, advanced reactors must demonstrate potential for delivery of products that are smaller, less capital-intensive, less risky, and more socio-politically attractive, and offering various generation options. Advanced reactors must also demonstrate more favorable costs, greater buy-in from competent and deep-pocketed energy infrastructure developers, and lower system integration and socio-technical risks than large reactors have been able to accomplish. The fact that large LWRs beyond the Vogtle reactors are not being considered in the United States today demonstrates a clear failure by the conventional industry to compete on those attributes. This is in contrast to other parts of the world where large-scale LWRs are being delivered on time and at costs that are competitive with other electricity generation options.

If the technical merits are insufficient to steer funds toward large-scale deployment, the proponent often turns to politics and policy for aid. But credibility matters in this sphere also. The policies on offer to support an emerging technology must be credible to an investor. Credibility is a multifaceted concept: credible incentives offer upfront rather than delayed support and they offer unconditional rather than conditional support.

Renewable energy technologies have succeeded over many years in securing production and investment tax credits and preferential take-off arrangements as part of a concerted effort to encourage the large-scale deployment of these energy resources. These policies have constituted credible signals to investors of policy support for these technologies; the prevalent messaging in favor of expanded renewable deployment certainly contributed to enhancing credibility as well. The availability of similar incentives for nuclear power in the Inflation Reduction Act (IRA) may have a similar impact on investor confidence in nuclear technology.

To lay the groundwork for expanded adoption of new and advanced nuclear reactors, it is necessary to consider three facts. First, credibility is key: it is the prism through which most investors assess low-carbon investment opportunities and the policy instruments that encourage deep decarbonization. Second, new and advanced nuclear reactors must strive to secure *credible* incentives if the goal is to boost investor interest. This might warrant less faith in politically fragile incentives that generate delayed benefits, like carbon pricing, and more faith in incentives that retire system risks, that serve to reduce the disincentive associated with capital intensity and that facilitate low-cost debt financing. The recent IRA may change this dynamic but only time will tell if the additional government support drives a change in investor confidence in the technology. Third, although investors might endorse the role of nuclear in decarbonization and may remain participants in the conversation surrounding nuclear power, they will be shrewd in their capital allocations even if they are proponents of the technology.

With these factors in mind, there is a need to confront various risks associated with the commercialization of advanced nuclear projects, and the future landscape in which they may play a role. Fundamentally, the projects must convincingly and honestly demonstrate that they can compete in a marketplace in which there are alternatives. For deployment in the United States, they must demonstrate a pathway to overcome the concerns that legitimately arise from the historical cost and schedule performance of previously built reactors. These commercialization risks are presented in Box 4-3.

BOX 4-3
Investor Risk Considerations

An investor contemplating an investment in the commercial deployment of an advanced reactor must evaluate a range of different risks:

Technology Risk. The demonstration of an advanced technology is anticipated to serve to retire most of the technical risks associated with that technology. Modifications could introduce new technical risks, and experience with the reactor over time may reveal new risks. These risks are described in Chapter 2.

Commercialization Risk. Even after a reassuring demonstration, there are challenges associated with commercial deployment, such as overcoming the project management cost and schedule delays that have plagued nuclear construction in the United States and Europe; establishing supply chains for fuel, parts, and components of sufficient quality, volume, and price; developing a sufficient order book to justify the establishment of a manufacturing facility; and ensuring the availability and cost of the necessary skilled workforce both for construction and operations. Commercial success may depend as well on international marketing. The project management, supply chain, and workforce challenges are discussed in Chapter 6 and the special problem of fuels is discussed in this chapter. The challenges associated with sales in international markets are discussed in Chapter 10.

Revenue Risk. The economic assessment must include an assessment of the revenue over the life of operations. There may be significant uncertainty in anticipated revenues over time, including risks that arise from competing technologies or from regulatory or policy changes. The revenue risk is discussed in this chapter, Chapter 3, and Chapter 5.

Regulatory Risk. The operator must obtain a license from the NRC after a thorough evaluation of both general and site-specific issues. While the design may be certified, there may be project-specific risks associated with NRC inspections, tests, analyses and acceptance criteria (ITAAC), or expensive backfits to deal with safety issues that arise during operations. Constraints arising from regulatory requirements will affect business plans, such as the plans for reduced staffing or to provide process heat to adjacent commercial users. Moreover, operation may require permits and rights-of-way from state and local governments. NRC regulatory issues are discussed in Chapter 7.

Infrastructure Risk. The success of a project may depend on the availability and cost of necessary infrastructure, such as the availability of transmission lines.

Financing Risk. The success of the project is dependent on access to equity and debt markets and the terms by which such financing is available, such as interest rates on debt. Financing is affected by the availability, extent, and reliability of incentives for commercial deployment, such as government loan guarantees or tax incentives. These matters are discussed in this chapter.

Reputational Risk. The investor must assess whether involvement in a nuclear project will pose a reputational risk with the investment community, shareholders, regulators, or other key stakeholders. These risks are discussed in Chapter 8.

Contract Risk. If nuclear vendors and EPC contractors are unwilling to offer contracts to buyers that cover (or at least share) completion risk, buyers may see other non-nuclear generation options as less risky. Knowing who will bear the risk if a project cannot be completed for whatever reason, especially for FOAK units, is essential. This is discussed in greater depth in Chapter 6.

SOURCE: Committee generated, following discussion with staff of the Energy Futures Initiative.

Two aspects bearing on the evaluation of the financial opportunity for advanced reactors require specific mention. First is the evaluation of the opportunities for nuclear power to provide alternative products. In an energy system with extensive renewables, nuclear power may be used to provide firm electricity generation at times when sufficient renewables are unavailable to meet grid needs. In such a situation, the economics of the plant can be highly dependent on whether other energy products—for example, industrial process heat, hydrogen and synfuels, or desalination—can be produced in the periods when the output of the nuclear plant is not dispatched to the grid.[12] Some vendors anticipate that their designs will be entirely devoted to these alternative products. The financial evaluation of these opportunities is particularly complex because it requires not only an understanding of the risks of the reactor and of any ancillary systems to produce the alternative product, but also of the future market for the alternate products. For example, the high-temperature output from an advanced reactor may be particularly well suited to produce hydrogen, but how large will the market for hydrogen be and within what time frame and at what price? These alternative products are discussed in more detail in Chapter 5.

Second, an evaluation of the opportunities for international sales may be an essential element in the evaluation of the financial opportunity for advanced nuclear reactors. All the vendors hope for substantial sales as a means to exploit learning to drive down costs. Some vendors anticipate factory production of reactors to reduce costs, enhance efficiency, and improve quality. But a large number of sales is required to justify the construction of a factory. In light of these considerations, the global market for a vendor's product must be part of the economic evaluation. This introduces additional complexity because it requires an understanding not only of the domestic market, but also an evaluation of the opportunities, competition, and incentives in foreign markets. International markets are discussed in detail in Chapter 10.

Government Incentives

There likely will be a need for government assistance in developing the finance structures and market incentives to help these emerging nuclear technologies make entry into the market. Some have argued that the federal government should refrain from establishing policies that influence the market. However, some targeted economic incentives may be necessary because the market does not always properly value certain important externalities such as climate change, system costs, and low emissions of other pollutants. As the advanced reactor technologies move beyond demonstrations, incentives may be necessary to enable advanced reactors to become an integral part of a carbon-free energy system in the United States. Such commercial incentives have allowed the penetration of renewables, and the same model should be followed for other low-carbon technologies, including advanced reactors.

These incentives and structures would need to be tailored for specific markets, and some may be more or less viable than others depending on prevailing market parameters. Deployment mechanisms exist that could create a clear and durable market signal for the commercialization of advanced reactors, several of which are briefly described below.

Loan Guarantees. Commercial lenders are often unwilling or unable to take on the risk of supporting the deployment of a new technology until it has a clear market demand and solid history of commercial operation. DOE is authorized to issue loan guarantees pursuant to Title 17 of the Energy Policy Act of 2005 (DOE n.d.).[13] Eligible projects for the Title 17 program must use a new or improved technology located in the United States that avoids, reduces, or sequesters greenhouse gases. In addition, the project needs to be credit worthy with a reasonable chance of repayment. Once the technology is proven at commercial scale through the first few projects, DOE stops providing financing and lets the private market take over. This program is intended to back investments that have financial risk, and some projects supported by the program should be expected to fail. To date, the DOE loan program has not lost money because the successful projects have more than compensated for the losses. Updates to the Loan Guarantee program were included in the Inflation Reduction Act of 2022. This included $40 billion in new loan guarantee authority–- which is available for nuclear facilities—and another $250 billion in loan

[12] A recent study by the OECD Nuclear Energy Agency provides context and significant detail about the viability of nuclear in co-generation, covering a wide range of alternatives such as hydrogen production, desalination, and district heating (NEA 2022).

[13] Details of the current program can be found in this DOE Fact Sheet (DOE 2020).

guarantee cap which is also available for some nuclear-related facilities. The Act also appropriated significant sums including $3.6 billion to cover borrowing costs and $5 billion for loan subsidies.[14]

Power Purchase Agreements (PPAs). The financial risk associated with an advanced reactor can be alleviated if the operator can obtain a long-term contract by which a customer agrees to pay for plant output at a specified price (e.g., $/MWh). This retires the risk associated with selling into a market with uncertain prices and offers potential customers with certainty that the output will be available at a specified price. In addition, the government (federal, state, or local) may help supplement the cost of power for the new energy technology by paying the differential cost above what would be current cost for proven energy technologies (e.g., natural gas) or may provide for a longer guaranteed period of purchase to incentivize the development of the new technology. There are challenges with the use of a PPA. If the customer is a government entity, most federal power purchase contracts (outside DoD) are currently limited to 10 years (GSA 2020), while lenders and facility owners might desire contracts as long as 40 years in order to be sure that they can recover their investment.[15]

Strike Price Agreement. This contractual vehicle is similar to a PPA and provides for a fixed price (strike price) for the electrical power supplied by the reactor. It is being used for the construction and eventual operation of an EDF European Pressurized Water Reactor (EPR) at Hinkley Point C (HPC) in the United Kingdom (Morison 2021). In strike price agreements, the government will supplement revenue based on this price if wholesale electricity prices are lower than this level, but the owner-operator will have to pay the government the price difference if wholesale prices are higher.

Investment Tax Credit. Investment Tax Credits have been used to benefit solar energy projects since 2006; currently 26 percent of the project cost (commercial or residential) can be used as a credit in 2021 (SEIA 2021). A significant portion of the cost of a solar energy project can be recovered as a credit against federal income taxes. The credit is not refundable, but it can be carried back for one year or carried forward for 20 years, enabling the credit to be applied in years in which the beneficiary has income taxes. Such an economic incentive is an obvious stimulus to investment in solar projects and could be applied to nuclear project investments as well.

Production Tax Credit. Production tax credits are fixed at a prespecified unit amount ($/MWh) and awarded for the quantity of electricity generated over a time span. Typically, an upper limit is set on the quantity of production that can receive the production credit. Payment is made when energy production occurs—for example, when electricity is sold onto the grid. The owner of the energy production facility (e.g., nuclear) receives both the current market price for the electricity and the supplementary production credit. This has proven to be a valuable incentive for renewable energy technologies like wind and solar (EPA 2020). The renewable production credits range from 13–25 $/MWh for a time span of 10 years (26 U.S.C. § 45J; NC Clean Energy Technology Center 2022).

A production credit rewards performance, with the result that the owner-operator bears the risk of building and operating the advanced reactor technology. If the advanced reactor is never completed, the supplementary production credit will not be earned. If the reactor is completed with delays or at greater cost than originally estimated, the size of the credit is not adjusted, and the developer and/or the owner earns a smaller profit or suffers a loss. This creates a strong incentive for private investors to guide the innovation process in the most cost-efficient direction.

The 2022 Inflation Reduction Act created a zero-emission nuclear power production tax credit (PTC) aimed at preventing the decommissioning of existing nuclear plants. The Nuclear PTC is available

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[14] As originally configured, the loan program required the applicant to pay an upfront fee to cover the risk of default. This significantly reduced the attractiveness of loan guarantees for novel projects that presented high risk. The loan subsidies cover this fee and thus make the loan program more attractive for applicants.

[15] Because the Defense Department already allows long-term PPAs (up to 30 years), consideration should be given to targeting the defense facility market as a leading opportunity for new designs. Carbon-free electricity has been a focus area across most military branches though most have not seriously considered a nuclear power alternative owing to lower peak demand which would make even an SMR too large in most cases (DOA 2022).

with respect to existing nuclear plants for electricity produced and sold for taxable years beginning after December 31, 2023, and before December 31, 2032.

The IRA also modified the U.S. tax code in a way that may allow advanced reactors to qualify for the technology-neutral clean electricity production tax credit (the Clean Electricity PTC). It does so by changing the definition of "qualified facility" to mean any plant that is placed into service after December 31, 2024, and produces zero greenhouse gas emissions. Because eligibility is based on emissions rates instead of generation technology, nuclear facilities may use the Clean Electricity PTC.

Last, the IRA established a Clean Hydrogen PTC. The Act funded the development of a number of clean hydrogen hubs around the country and at least one of them must use nuclear power to produce clean hydrogen.

Construction Work in Progress (CWIP). The recovery of the costs of an NPP in most regulated markets commences once the plant goes into operation. That is, the recovery of all the costs for constructing and operating the plant are recovered in the rates paid by rate payers during operations. These costs thus include the substantial interest costs that have been accrued over the many years of construction. If recovery of interest costs from ratepayers during the period before a plant goes into operation is allowed, the total cost of the plant is reduced (through the elimination of the interest on the interest) and some of the risk of the project is shifted from the investors to the ratepayers. CWIP has often proved unpopular with ratepayers because it serves to shift risk and results in increased rates before there is contemporaneous electricity production from the nuclear plant. Ratepayer education and buy-in is extremely important to utilize this financial tool. The Vogtle plant has the benefit of recovery of CWIP, subject to some limitations imposed by the Georgia Public Utility Commission.

IRA Energy Communities. The Inflation Reduction Act provides a 10 percent enhancement of tax credits for clean-energy projects in an "energy community." Among several criteria of eligibility for this bonus is a project be located in a census tract within which a coal power plant has closed since 2010. Several vendors of advanced reactors have examined the siting of new reactors at retired coal plants and these coal-to-nuclear projects may be eligible for this enhancement of tax credits.

Carbon Tax or a Clean Energy Portfolio. In principle, equal treatment of a wide range of energy technologies could be implemented through a uniform carbon tax or through a requirement to deploy a portfolio of clean energy technologies. Various social costs have been associated with the production of CO_2 (EPA 2021), and multiple proposals have been offered to either tax carbon emissions or otherwise provide incentives for technologies that do not emit CO_2.[16] As noted above in the section on Production Tax Credits, the recent passage of the IRA finally placed nuclear on a level playing field with respect to other low carbon generators. Despite strong proponents, it has proven politically impossible to establish a carbon tax. And a carbon tax or a portfolio standard has the disadvantage that it favors established technologies, whereas a focused program of technology-related incentives creates new options. The IRA reflects a welcome signal by the Congress to facilitate a transition to a low carbon future by providing incentives for *all* low-carbon technologies while avoiding the political difficulties associated with a tax.

Recommendation 4-4: To enable a cost-competitive market environment for nuclear energy, federal and state governments should provide appropriately tailored financial incentives (extending and perhaps enhancing those provided recently in the Inflation Reduction Act) that industry can use as part of a commercialization plan, consistent with the successful incentives provided to renewables. These tools may vary by state, locality, and market type.

[16] In January 2021, President Biden issued E.O. 13990, which reestablished the Intergovernmental Working Group (IWG) and directed it to ensure that SC-GHG estimates used by the U.S. government reflect the best available science and recommendations of the National Academies (2017) and work toward approaches that take account of climate risk, environmental justice, and intergenerational equity. The guidelines supporting the execution of the new EO are covered in Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990.

Continued evaluation of the recently passed incentives will need assessment to determine their adequacy. The scale of these incentives needs to be sufficient not only to encourage nuclear projects but also the vendors and the supporting supply chains.

REFERENCES

26 U.S. Code § 45J—Credit for Production from Advanced Nuclear Power Facilities. 2014. https://www.law.cornell.edu/uscode/text/26/45J.

Abdulla, A., M.J. Ford, M.G. Morgan, and D.G. Victor. 2017. "A Retrospective Analysis of Funding and Focus in U.S. Advanced Fission Innovation." *Environmental Research Letters* 12(8):084016. https://doi.org/10.1088/1748-9326/aa7f10.

American Nuclear Society Task Force on Public Investment in Nuclear Research and Development. 2021. *The U.S. Nuclear R&D Imperative*. La Grange Park, IL: American Nuclear Society. https://www.ans.org/file/3177/2/ANS%20RnD%20Task%20Force%20Report.pdf.

Bistline, J. 2021. *Powering Decarbonization: Strategies to Achieve Net-Zero Emissions in the Electric Sector and Beyond*. Palo Alto, CA: Electric Power Research Institute.

Black and Veatch. 2012. *Cost and Performance Data for Power Generation Technologies*. Black & Veatch Holding Company.

Boardman, R., C. Rabiti, S. Hancock, D. Wendt, K. Frick, S. Bragg-Sitton, H. Hu, et al. 2019. *Evaluation of Non-Electric Market Options for a Light-Water Reactor in the Midwest. Light Water Reactor Sustainability Program*. Idaho Fall, ID: Idaho National Laboratory. https://doi.org/10.2172/1559965. INL/EX—19-55090-Rev000.

Buongiorno, J., M. Corradini, J. Parsons, and D. Petti. 2018. *The Future of Nuclear Energy in a Carbon-Constrained World*. Cambridge, MA: Massachusetts Institute of Technology Energy Initiative.

Chemnick, J. 2021. "Cost of Carbon Pollution Pegged at $51 a Ton." *Scientific American; E&E News*, March 1. https://www.scientificamerican.com/article/cost-of-carbon-pollution-pegged-at-51-a-ton.

Clack, C.T.M., A. Choukulkar, B. Coté, and S.A. McKee. 2022. *Role of Electricity Produced by Advanced Nuclear Technologies in Decarbonizing the U.S. Energy System*. Boulder, CO: Vibrant Clean Energy.

Demick, L.E. 2011. *NGNP Project 2011 Status and Path Forward*. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1035900. INL/EXT-11-23907.

DOA (Department of the Army), Office of the Assistant Secretary of the Army for Installations, Energy and Environment. 2022. "United States Army Climate Strategy." Washington, DC. https://www.army.mil/e2/downloads/rv7/about/2022_army_climate_strategy.pdf.

DOE (Department of Energy). 2020. "Advanced Nuclear Energy Loan Guarantees." Department of Energy Loan Programs Office. https://www.energy.gov/sites/default/files/2020/01/f70/DOE-LPO-Nuclear-Energy-Jan2020.pdf.

DOE. 2021. "Budget (Justification and Supporting Documents)." https://www.energy.gov/cfo/listings/budget-justification-supporting-documents.

DOE. n.d. "Advanced Nuclear Energy Projects Loan Guarantees." https://www.energy.gov/lpo/advanced-nuclear-energy-projects-loan-guarantees.

DOE-NE (Office of Nuclear Energy). 2010. *Next Generation Nuclear Plant: A Report to Congress*. Washington, DC: Department of Energy.

EIA (U.S. Energy Information Administration). 2014. *Behavioral Economics Applied to Energy Demand Analysis: A Foundation*. Washington, DC: Department of Energy.

EIA. 2019. *International Energy Outlook 2019 with projections to 2050*. Washington, DC: U.S. Energy Information Administration.

EIA. 2020. *Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies*. Washington, DC: Energy Information Administration.

EIA. 2021. *Electric Power Annual 2020*. Washington, DC: U.S. Energy Information Administration.
EIA. 2022. "Monthly Energy Review: Table 7.2a: Electricity Net Generation: Total (All Sectors)." https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T07.02A#/?f=A.
EPA (U.S. Environmental Protection Agency). 2015. "Fact Sheet: Clean Power Plan–- Opportunities for Nuclear Power." https://archive.epa.gov/epa/cleanpowerplan/fact-sheet-clean-power-plan-opportunities-nuclear-power.html.
EPA. 2016. "Social Cost of Carbon Fact Sheet." https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon-fact-sheet.
EPA. 2020. "Renewable Electricity Production Tax Credit Information." https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information.
EPRI (Electric Power Research Institute). 2016. *Advanced Nuclear Technology: Using Technology for Small Modular Reactor Staff Optimization, Improved Effectiveness, and Cost Containment.* 3002007071. Palo Alto, CA: Electric Power Research Institute.
EPRI. 2017. *Program on Technology Innovation: Expanding the Concept of Flexibility for Advanced Reactors, Refined Criteria, a Proposed Technology Readiness Scale, and Time-Dependent Technical Information Availability*. 3002010479. Palo Alto, CA: Electric Power Research Institute.
EPRI. 2018. *Exploring the Role of Advanced Nuclear in Future Energy Markets: Economic Drivers, Barriers, and Impacts in the United States*. 3002011803. Palo Alto, CA: Electric Power Research Institute.
Eurostat. 2022. "Nuclear Energy Statistics." https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Nuclear_energy_statistics.
Ford, M.J., and Schrag, D.P. 2019. "The Case for a Tortoise Approach to U.S. Nuclear Research and Development." *Energy Policy*, 135(December):111013. https://doi.org/10.1016/j.enpol.2019.111013.
Ford, M.J., A. Abdulla, M.G. Morgan, and D.G. Victor. 2017. "Expert Assessments of the State of U.S. Advanced Fission Innovation." *Energy Policy* 108(September):194–200. https://doi.org/10.1016/j.enpol.2017.05.059.
GSA (U.S. General Services Administration). 2020. "For Federal Agency Customers." https://www.gsa.gov/real-estate/environmental-programs/energy-water-conservation/areawide-public-utility-contracts/for-federal-agency-customers.
Ingersoll, E., K. Gogan, J. Herter, and A. Foss. 2020a. *Cost and Performance Requirements for Flexible Advanced Nuclear Plants in Future U.S. Power Markets*. Report for the ORNL Resource team supporting ARPA-E's MEITNER Program. LucidCatalyst LLC. https://doi.org/10.2172/1646858.
Ingersoll, E., K. Gogan, J. Herter, and A. Foss. 2020b. *The ETI Nuclear Cost Drivers Project: Full Technical Report*. Energy Systems Catapult and LucidCatalyst. https://www.lucidcatalyst.com/eti-nuclear-cost-drivers-full.
INL (Idaho National Laboratory). 2004. *U.S. Job Creation Due to Nuclear Resurgence in the United States.* Idaho Falls: Idaho National Laboratory.
INL. 2008. *Next Generation Nuclear Plant Project Preliminary Project Management Plan*. PLN-2489; INL/EXT-05-00952. Idaho Falls, ID: Idaho National Laboratory.
INL. 2022. "Systems Analysis and Integration." https://fuelcycleoptions.inl.gov/SitePages/CostBasisReport.aspx.
Jenkins, J.D., and N.A. Sepulveda. 2017. *Enhanced Decision Support for a Changing Electricity Landscape: The GenX Configurable Electricity Resource Capacity Expansion Model*. Cambridge, MA: Massachusetts Institute of Technology Energy Initiative.
Jenkins, J.D., Z. Zhou, R. Ponciroli, R.B. Vilim, F. Ganda, F. de Sisternes, and A. Botterud. 2018. "The Benefits of Nuclear Flexibility in Power System Operations with Renewable Energy." *Applied Energy* 222(July):872–884. https://doi.org/10.1016/j.apenergy.2018.03.002.
Kahneman, D., and I. Ritov. 1994. "Determinants of Stated Willingness to Pay for Public Goods: A Study in the Headline Method." *Journal of Risk and Uncertainty* 9(1):5–37.
Kim, S.H. 2022. *Scenarios of Nuclear Energy Use in the United States for the 21st Century*. PNNL-33234.

Krishnan, M., H. Samandari, J. Woestzel, S. Smit, D. Patchod, D. Pinner, et al. 2022. *The Net Zero Transition: What It Would Cost, What It Could Bring.* McKinsey & Company. https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/the%20net%20zero%20transition%20what%20it%20would%20cost%20what%20it%20could%20bring/the-net-zero-transition-executive-summary.pdf?shouldIndex=false

Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, et al. 2021. *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*. Final Report. Princeton, NJ: Princeton University Press. https://www.dropbox.com/s/ptp92f65lgds5n2/Princeton%20NZA%20FINAL%20REPORT%20%2829Oct2021%29.pdf?dl=0.

Lo, C. 2020. “Could the Regulated Asset Base Model Unlock UK Nuclear?” *Power Technology*. Originally published November 14, 2019; updated July 15, 2020. https://www.power-technology.com/features/regulated-asset-base-model-uk-nuclear.

Longnecker and Associates. 2012. *Nuclear Power 2010 Program: Combined Construction and Operating License and Design Certification Demonstration Projects Lessons Learned Report.* Washington, DC: Department of Energy.

Lovering, J., et al. 2020. “Chasing Cheap Nuclear: Economic Trade-Offs for Small Modular Reactors.” *The Bridge* 50(3):40–46. https://www.nae.edu/239267/Chasing-Cheap-Nuclear-Economic-TradeOffs-for-Small-Modular-Reactors.

Morison, R. 2021. “U.K. Power Is So High That EDF Hinkley Reactor Looks Good Value.” *Bloomberg.Com*, July 30. https://www.bloomberg.com/news/articles/2021-07-30/u-k-power-is-so-high-that-edf-hinkley-reactor-looks-good-value.

NASA (National Aeronautics and Space Administration). 2021. “Technology Readiness Level.” https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

NASEM (National Academies of Sciences, Engineering, and Medicine). 2022. *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.

National Research Council. 2008. *Review of DO''s Nuclear Energy Research and Development Program*. Washington, DC: The National Academies Press. https://doi.org/10.17226/11998.

NC Clean Energy Technology Center. 2022. “Renewable Electricity Production Tax Credit (PTC).” https://programs.dsireusa.org/system/program/detail/734.

NEA (Nuclear Energy Agency). 2022. *Beyond Electricity: The Economics of Nuclear Cogeneration*. NEA No. 7363. Paris: Organisation for Economic Co-Operation and Development.

Nicholson, W., and C. Snyder. 2012. *Microeconomic Theory: Basic Principles and Extensions*. 11th ed. Mason, Ohio: South-Western/Cengage Learning.

NRC (Nuclear Regulatory Commission). 2021a. “NRC Issues License to Interim Storage Partners for Consolidated Spent Nuclear Fuel Interim Storage Facility in Texas.” *NRC News*, September 13. https://www.nrc.gov/reading-rm/doc-collections/news/2021/21-036.pdf.

NRC. 2021b. “Consolidated Interim Storage Facility (CISF)” https://www.nrc.gov/waste/spent-fuel-storage/cis.html.

Nuclear News. 2021. “Trillion-Dollar Infrastructure Bill Passes House.” *Nuclear Newswire*, November 8. https://www.ans.org/news/article-3413/trilliondollar-infrastructure-bill-passes-house.

NuScale. 2021. *NuScale SMR Technology An Ideal Solution for Repurposing U.S. Coal Plant Infrastructure and Revitalizing Communities.*

Petti, D., R. Hill, J. Gehin, H. Gougar, G. Strydom, T. O’Connor, F. Heidet, et al. 2017. “A Summary of the Department of Energy’s Advanced Demonstration and Test Reactor Options Study.” *Nuclear Technology* 199(2):111–28. https://doi.org/10.1080/00295450.2017.1336029.

Ritchie, H., and M. Roser. 2020. “Energy.” Our World in Data. https://ourworldindata.org/energy.

Savage, I. 1993. “Demographic Influences on Risk Perceptions.” *Risk Analysis* 13(4):413–420. https://doi.org/10.1111/j.1539-6924.1993.tb00741.x.

SEIA (Solar Energy Industries Association). 2021. “Solar Investment Tax Credit (ITC).” https://www.seia.org/initiatives/solar-investment-tax-credit-itc.

St. John, J. 2020. “7 Transmission Projects That Could Unlock a Renewable Energy Bounty.” *Greentech Media*, April 9. https://www.greentechmedia.com/articles/read/9-transmission-projects-laying-the-paths-for-cross-country-clean-energy.

Talabi, S.M. and P. Fischbeck. 2015, “Advancing Risk Management in Nuclear Power Plant EPC Projects: An Empirical Evaluation of Risk Management Practices on Steam Generator Replacement Projects.” Pp. 545–557 in *Proceedings of the 7th World Congress on Engineering Asset Management*, edited by W.B. Lee, B. Choi, L. Ma, and J. Mathew. https://doi.org/10.1007/978-3-319-06966-1_49.

U.S. DOE Nuclear Energy Research Advisory Committee and Gen IV International Forum. 2002. *A Technology Roadmap for Generation IV Nuclear Energy Systems*. GIF-002-00. https://www.gen-4.org/gif/jcms/c_40481/technology-roadmap.

World Nuclear Association. 2022. “Economics of Nuclear Power Economics.” https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx.

5

Beyond Electricity: Nuclear Power's Potential to Play a Broader Role in the Future Energy System

Decarbonizing the electric power sector is necessary to avert the worst consequences of climate change, but it is not sufficient: energy-related carbon dioxide emissions extend to the buildings, transportation, and industrial sectors as well. Some of these sectors cannot be electrified for technical reasons, or it might be cost-prohibitive to do so. New and advanced nuclear power technologies have the potential to provide a range of energy services other than electricity. For example, they produce large amounts of heat that can be leveraged for useful purposes: either nuclear electricity or nuclear heat can be used to desalinate water or produce synthetic fuels[1] like hydrogen, ammonia, and gaseous and liquid hydrocarbons. If carbon constraints tighten, and as the energy system begins transitioning to one that better values some of these other services, nuclear reactors have the potential to decarbonize non-electric but carbon-intensive sectors of the economy. However, employing nuclear power for these novel applications raises serious technical, economic, and regulatory challenges that must be resolved for any expanded deployment to be realized. This chapter will briefly describe these non-electric applications, how the reactors discussed in this report could serve them, and the significant emergent challenges that must be resolved.

APPLICATIONS BEYOND ELECTRICITY

As shown by Figure 5-1, buildings, transportation, and industrial sectors all are substantial users of energy and emitters of greenhouse gases, and some of that demand is in the form of thermal energy, which could be produced without electricity. Because nuclear reactors produce substantial amounts of heat, their services could expand beyond the electricity sector. With advanced reactor output temperatures up to 800°C, a wide range of non-electric services is possible; some are listed in Table 5-1. Broadly, these services can be clustered into three categories: industrial products, district heating, and water desalination.

[1] There are several different definitions of the term synthetic fuel. The more traditional definitions refer to synthetic fuels as any liquid transportation fuels produced from coal, natural gas, or biomass feedstocks through chemical conversion. Other definitions also include industrial and municipal waste as well as oil sands and oil shale as synthetic fuel sources. Depending on the context, hydrogen, ammonia, methanol, and ethanol can also be referred to as synthetic fuels.

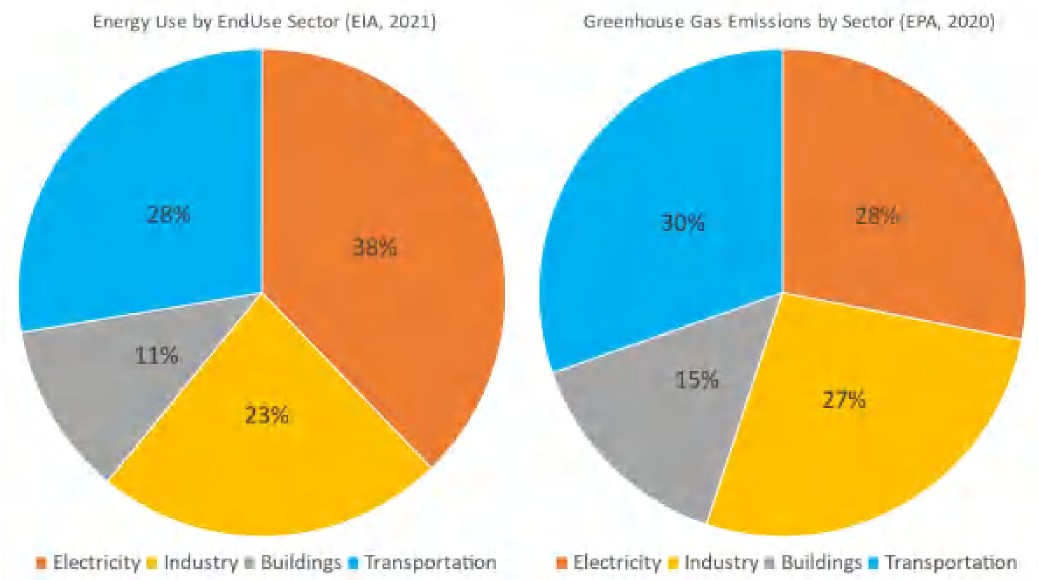

FIGURE 5-1 U.S. energy use by end-use sector, 2021, and greenhouse gas emissions by sector, 2020. Total energy use in 2021 was 97.33 quads. Total greenhouse gas emissions in 2020 was ~5,200 MMT CO_{2e} (inclusive of the ~700 MMT CO_{2e} net sink from land use and forestry).
SOURCES: Committee generated using data from U.S. Energy Information Administration, 2021, *Annual Energy Outlook 2021*, Washington, DC; U.S. Environmental Protection Agency, 2020, "Renewable Electricity Production Tax Credit Information," https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information.

TABLE 5-1 Possible Energy Products Provided by Nuclear Energy Systems

Energy Service	Elaboration on Technical Readiness	Temperature Range (°C)
Industrial products		
Hydrogen	Multiple hydrogen production pathways exist, and electrolysis of water is among the most mature technological pathway for clean hydrogen production. The three most common electrolysis technologies are alkaline,[a] polymer electrolyte membrane (PEM) and solid oxide electrolysis cell (SOEC). PEM electrolysis requires electricity, and the systems operate at ~100°C. SOECs require both electricity and heat, and the systems operate at temperatures of between 500°C and 1000°C. Hundreds of high-temperature thermochemical splitting cycles have been proposed; they require temperatures of between 500°C and 2000°C, making them most suitable to integrate with non-LWRs. High-temperature systems also require the development of improved heat exchangers.	~100 (PEM) 500–1,000 (SOEC) 500–2,000[b] (thermochemical splitting)
CO_2 reduction to fuels	The production of carbon-neutral synthetic liquid fuels (e.g., diesel, jet fuel, motor gasoline) would entail the electrocatalytic reduction of carbon dioxide. It also requires hydrogen, water, electricity, and heat. Moreover, it requires the integration of the nuclear reactor with SOECs, a Fischer-Tropsch process or a Mobil process, and balance of plant components (such as distillation units).	500–1,000

High-temperature process heat	Required for ammonia synthesis and steam methane reforming. To meet process heat needs, materials and components such as heat exchangers must be developed that work at these temperatures.	>500
Lower-temperature process heat	Required for paper and pulp manufacturing. Moreover, many chemical applications (including many separation processes) require thermal energy at temperatures below 250°C.	~300
Steel production	Thermal energy is required to preheat iron ore pellets to approximately 850°C: some advanced nuclear reactors could directly provide heat at that temperature, or power electrified steel production equipment.	~850
Cement production	Cement production is a complex process that involves three distinct steps for converting limestone-bearing feed: (1) preheating from room temperature to approximately 660°C; (2) calcination of calcium carbonate at approximately 900°C; (3) calcination completion and sintering of calcium oxide up to approximately 1450°C. Thermal output from advanced nuclear is directly suitable for preheating the limestone-bearing feed and is almost at the temperature ranges required for the calcination process. Heat augmentation is required to provide the thermal energy required to complete the calcination and sintering processes.	660–1,450
District energy	District energy network technology is mature, but proximity to the community is essential, because heat cannot be transported over long distances. All reactor concepts are suitable with a low temperature heat extraction loop. Alternatively, community space and water heating can be electrified with large amounts of low-carbon electric power from nuclear power.	80–100
Water desalination	Multiple desalination systems are technologically mature and are declining in cost. Multi-stage flash distillation (MSF) requires temperatures of 70°C to 130°C. Reverse osmosis (RO) requires electricity, rather than thermal energy: the output of RO systems is diminished at both low (<10°C) and high temperatures (>38°C). All reactor concepts are suitable with a low temperature heat extraction loop.	70–130 (MSF) <38 (RO)

[a] Alkaline water electrolysis has the longest history and is currently the cheapest among all the water electrolysis technologies for hydrogen production. However, the system efficiency and hydrogen purity deteriorate when the technology is subject to flexible operations making it harder to integrate with variable renewable sources and a future grid with substantial amounts of variable generations. Thus, it is not the focus of this chapter.

[b] Note that advanced reactors would require heat augmentation to provide the total thermal energy for applications that require temperatures that are higher than their outlet temperatures.

SOURCES: Committee generated using information from R.D. Boardman, M.G. McKellar, B.D. Dold, A.W. Foss, and H.C. Bryan, 2021, "Process Heat for Chemical Industry," *Encyclopedia of Nuclear Energy* 3, https://doi.org/10.1016/b978-0-12-819725-7.00198-7; S.M. Bragg-Sitton, C. Rabiti, R.D. Boardman, et al., 2020, *Integrated Energy Systems: 2020 Roadmap*, INL/EXT-20-57708-Rev.01, Idaho Falls, ID: Idaho National Laboratory, https://doi.org/10.2172/1670434; M. Fisher, A. Constantin, and J. Liou, 2021, "The Use of Nuclear Power Beyond Generating Electricity: Non-Electric Applications," IAEA, October 18, https://www.iaea.org/newscenter/news/the-use-of-nuclear-power-beyond-generating-electricity-non-electric-applications; M.A. Rosen, 2020, "Nuclear Energy: Non-Electric Applications," *European Journal of Sustainable Development Research* 5(1):em0147, https://doi.org/10.29333/ejosdr/9305.

Whether nuclear power can be used for a service beyond electricity, and which reactor type is most technically appropriate, depends mainly on the temperature required for the application. Figure 5-2 displays the temperature requirements for various uses of the heat from a reactor. Note that collocation of the reactor and the industrial/heat application is necessary as heat cannot be transported over long distances and siting restrictions could impede the deployment of a nuclear reactor to serve some applications. This requires thoughtful consideration and analysis because the reactor may impose risk on the adjacent facility using the heat, and there may be a risk to the nuclear plant arising from that facility which may involve hazardous materials itself. This confluence of risks introduces additional regulatory challenges when it comes to siting, the development of emergency planning zones, and emergency response.

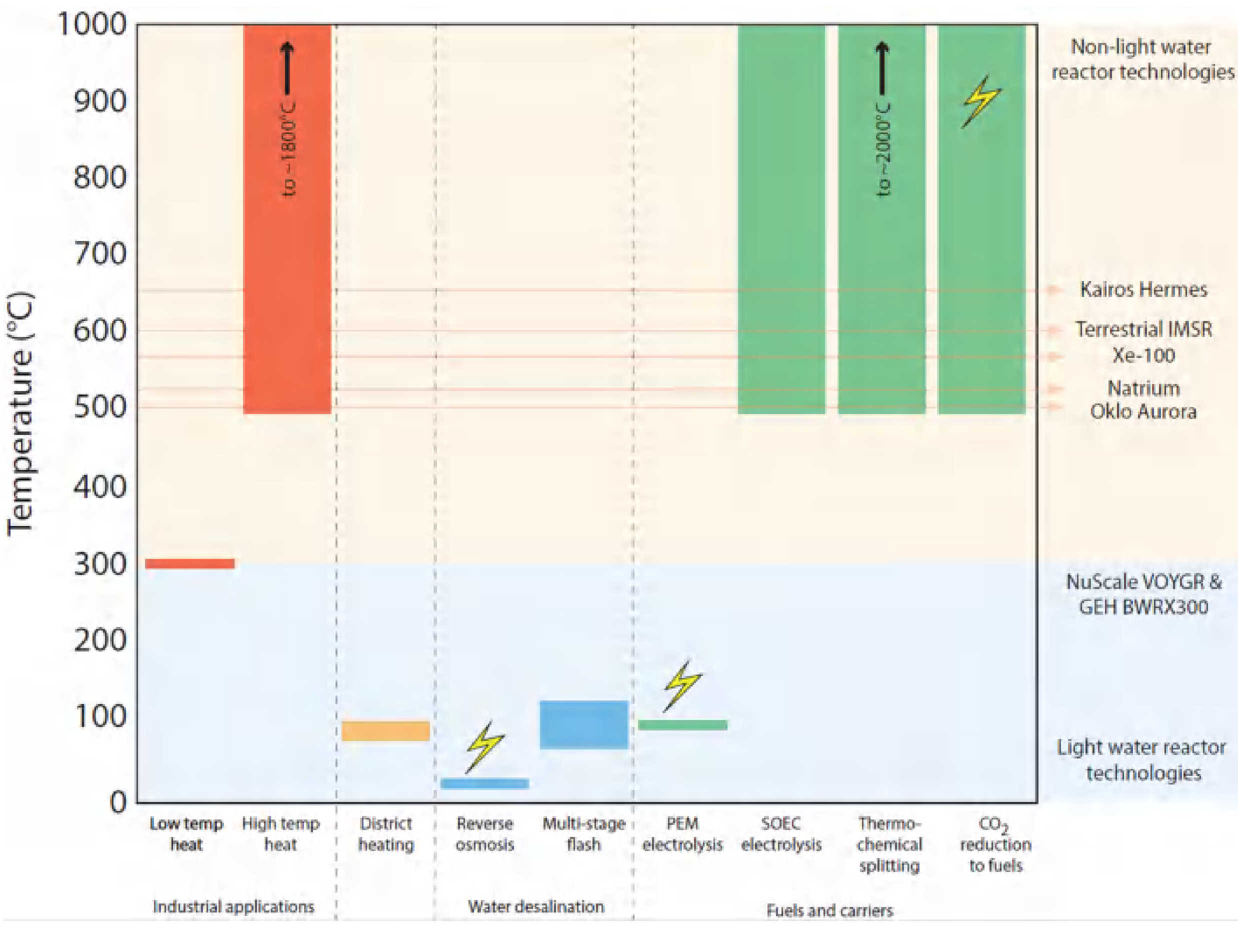

FIGURE 5-2 New and advanced nuclear reactors can provide a range of non-electric services to the energy system.
NOTES: The figure shows the temperature ranges of some of these non-electric energy services. Note that many processes require both electricity and heat to operate: lightning bolt symbols indicate processes that rely exclusively on electrical energy, rather than thermal energy.

In principle, none of these potential industrial applications is novel: the Department of Energy had a Nuclear Hydrogen Initiative at the turn of the century, when climate change grew in prominence as a topic of public and political debate. A robust narrative was constructed around a "hydrogen economy" (Tseng et al. 2005; Scita et al. 2020); once interest in hydrogen dissipated, the interest in leveraging nuclear for hydrogen production also diminished. Moreover, some nuclear power plants (NPPs) already supply heat to district heating systems. What *is* new is the higher temperatures that some advanced nuclear systems could provide, the potential cost reductions that might be achieved through innovative design and manufacturing processes, and the growing interest in integrating non-electric energy services so that nuclear reactors might better compete in a power system that is increasingly served by variable renewable energy resources.

Multiple paradigms are envisioned that integrate non-electric applications into future nuclear reactor deployments. Whenever nuclear reactors are combined into larger systems that are intended to produce products other than heat or electricity, the combined systems are called integrated energy systems (IES).[2] NPPs could be deployed to exclusively provide energy services to industrial customers, instead of dispatching electricity to the grid. In this scenario, they could be dedicated to heat production (e.g., for petrochemical facilities), hydrogen generation (e.g., to serve petrochemical, the industrial, heating, or transportation sectors), or ammonia and synthetic fuels production. Alternatively, an NPP could be deployed to produce electricity to the grid as well as other products such as hydrogen. Insofar as electricity is concerned, these integrated energy systems would provide the flexibility to dispatch electricity to the grid while taking advantage of grid price signals by ramping up and down energy supplies to the industrial processes. These load following capabilities have the potential to enhance grid reliability and could allow reactors to gain an additional revenue stream in selling another product such as hydrogen. The economic viability of these grid-integrated systems will vary significantly by location and products.

For these integrated energy system concepts to work, alignment and coordination is required among facilities, some of which might be owned and operated by different (or even competing) firms. Also, important to consider is that the investment and development cycles of different industrial facilities differ—refineries can last a century, chemical plants decades, and fuel cell stacks are short-lived—making coordinated and synergistic investment in NPPs to serve those facilities' energy needs necessary and potentially challenging. This challenge is not insurmountable, but it is extremely serious, and efforts must be made to ensure that the interests of companies that are investing in an integrated plant are aligned and will remain so for the long lifetime of a nuclear reactor.

The following subsections briefly describe potential non-electric applications: clean hydrogen, ammonia and synthetic fuels production, industrial process heat, district heating, and water desalination. As discussed in Box 5-2, there may be opportunities to reconfigure some current uses of energy in more radical ways than are discussed here to curtail carbon emissions.

Finding 5-1: In principle, nuclear power has the versatility to provide a range of non-electric services to the whole energy system. These services themselves need to be decarbonized, and the emissions of some could prove hard to abate without a high-temperature, zero-carbon energy source, such as nuclear power. Moreover, experience exists and is growing that some of these services can be provided with nuclear power.

Recommendation 5-1: Industrial applications using thermal energy present an important new mission for advanced reactors. Key research and development needs for industrial applications include assessing system integration, operations, safety, community acceptance, market size as a function of varying levels of implicit or explicit carbon price, and regulatory risks, with hydrogen production as a top priority. The Department of Energy, with the support of industry support groups such as the Electric Power Research Institute and the nuclear vendors, should conduct a systematic analysis of system integration, operation, and safety risks to provide investors with realistic models of deployment to inform business cases and work with potential host communities.

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[2] For more on Integrated Energy Systems see Integrated Energy Systems, 2023, "What Are Integrated Energy Systems," ies.inl.gov.

Nuclear–Hydrogen Integrated Energy Systems and Their Potential Role in Deep Decarbonization

Hydrogen has the potential to enable decarbonization in almost all sectors of the economy. It can be directly employed either in a fuel cell or combustion turbine to produce electricity or can provide long-duration energy storage that enhances the reliability and resilience of the future power system. It can be combusted to produce thermal energy or can be used as a chemical feedstock. It is already used in a variety of manufacturing processes, including petroleum refineries, chemicals, metal refining, steel, and ammonia production. More importantly, it can be applied in the future in sectors of the energy system that are difficult or expensive to electrify, such as some industrial processes and some elements of the transportation system that require a carbon-neutral synthetic fuel (e.g., heavy-duty trucks, marine transport, and aircraft).

Hydrogen could also be phased into the existing gas system, first by blending it into natural gas pipelines (up to 20 percent hydrogen by volume without any major modifications[3]), and then by converting pipelines and end use systems to use 100 percent hydrogen (technologies for pipelines and turbines already exist). This would allow hydrogen to contribute to decarbonization of sectors beyond electric power generation as a replacement for natural gas.

Elemental hydrogen (H_2) does not occur naturally in the earth. Rather, it is chemically bound to other elements, and energy must be used to break chemical bonds such as those forming methane (CH_4) or water (H_2O) to obtain elemental hydrogen. Currently, most hydrogen worldwide is produced using steam methane reforming, a process in which natural gas is heated in the presence of steam and a catalyst to produce carbon monoxide and hydrogen. The carbon monoxide is then converted to CO_2 and emitted into the atmosphere. According to the IEA, currently the global hydrogen production releases 830 million tons of CO_2 per year, which accounts for 2.2 percent of total energy-related emissions. For hydrogen to contribute to the net-zero transition, it must be produced at much lower carbon intensities than this. Fortunately, there are multiple low-carbon hydrogen production pathways (see Table 5-1 for some of the most promising clean hydrogen production technologies enabled by nuclear energy): this versatility makes nuclear production of hydrogen a promising means for decarbonizing industry, transportation, and buildings.

Driven by their long-term decarbonization goals, major economies such as the United States, Canada, and the European Union have envisioned an overarching role for hydrogen in low-carbon energy systems by mid-century, reflected in their governmental hydrogen roadmaps (DOE 2020a; EC 2020; NRC 2020). Indeed, the global hydrogen market is expected to grow from around 90 MT to more than 500 MT by 2050 (IEA 2021b). Table 5-2 presents some key hydrogen demand streams that are being envisioned.

Hydrogen produced by NPPs could potentially meet some of these demands. Hydrogen may be produced at an NPP at a central location and delivered to its end users through dedicated pipelines or other means of transport. Nuclear reactors may also be co-located with the industrial customer to produce hydrogen on-site, for example to replace the steam methane reforming process (Nuclear Newswire 2022). Given the smaller footprint and potentially reduced cost of future reactors, the latter deployment scenario may be promising.

TABLE 5-2 Potential Hydrogen Use Cases and Demand Trends in a Decarbonized United States

Use Case	Description
Fuel cell electric vehicles (FCEVs)	FCEVs could witness some level of market penetration, alongside battery electric vehicles (BEVs). Compared to BEVs, FCEVs could enable longer-range travel, higher power[a] and faster recharge rates. Medium and heavy-duty vehicles could transition to hydrogen use before light-duty vehicles.

[3] Hydrogen blends above 5 percent could cause pipeline degradation and leaks.

Blending hydrogen with natural gas	Hydrogen can be injected into existing natural gas pipelines to reduce the fuel's carbon intensity. Up to 20% hydrogen (by volume) can be mixed with natural gas in existing pipelines without major modifications to the pipelines. There are ongoing R&D efforts to develop combustion turbines and appliances that can handle hydrogen concentrations of up to 100%—some of these technologies are already available—which would require hydrogen-compatible pipeline infrastructure. According to the IEA's net-zero scenario, the demand for hydrogen blended in natural gas sees the greatest growth among all sectors between 2020 and 2030 (IEA 2021b). However, there are different views on this potential hydrogen uptake in the literature: its evolution could depend on the success of demonstration projects (FCH JU 2019).
Petroleum refineries	Petroleum refineries are the most significant users of hydrogen today. About two-thirds of the hydrogen needed at U.S. petroleum refineries is produced onsite using steam methane reforming. Hydrogen is primarily used for hydrocracking and hydrotreating to upgrade crude oil to distillates like gasolines, diesel fuels, or jet fuels. This use of hydrogen could decline in the future if fossil fuel use declines.
Direct reduced iron for metal refining and steel production	The direct reduction of iron (DRI) uses natural gas as a reducing agent and then converts the high-purity iron to steel in an electric arc furnace (EAF). However, up to 30% hydrogen by energy can be blended with natural gas without major modification to plant design, reducing CO_2 emissions. Also, DRI designs exist which use 100% hydrogen as the reducing agent (Hybrit n.d.). In the United States, the amount of steel produced by DRI-EAF in 2017 already accounted for 68% of its total production. The iron and steel sectors are expected to grow (IEA 2019a), and the provision of clean hydrogen for DRI-EAF could help decarbonize these sectors.
Ammonia and fertilizers	Ammonia is produced by the Haber-Bosch process, which reacts hydrogen and nitrogen at high temperatures and pressures. The hydrogen is derived through steam methane reforming. Currently, most domestic ammonia is intended for fertilizers, and this demand stream is not expected to grow in the coming years, thanks to increases in nitrogen fertilizer efficiency. However, there could also be a potential market for ammonia as a hydrogen energy carrier, as it is more easily stored and transported in liquid form than hydrogen. Ammonia's toxicity and the production of criteria air pollutants from its emission or combustion are significant concerns to be addressed.
Carbon-neutral synthetic fuels	Currently, high-demand synthetic fuels like methanol, transportation fuels (diesel, jet fuel, motor gasoline), and dimethyl ether (DME) are predominantly produced using fossil fuels as the feedstock and energy source. Gasification or steam methane reforming first converts fossil fuels into syngas (a mix of carbon monoxide and hydrogen), which is then converted to synthetic fuels through processes such as Fisher-Tropsch. Co-electrolysis can produce hydrogen using high-purity CO_2, water, electricity and possibly heat powered by clean energy sources to reduce the carbon emissions of the synthetic fuel manufacturing process. The global market for synthetic fuels is expected to grow, and methanol alone has potential growth in multiple uses such as petrochemicals and fuel blending. Carbon-neutral synthetic fuels could help decarbonize parts of the transportation sector. Synthetic fuels represent medium- to long-term opportunities. For example, the European Union's hydrogen roadmap expects them to reach mass-market penetration by 2040 in its ambitious scenario (FCH JU 2019).

[a] Liquid hydrogen is approximately 100 times more energy dense than lithium-ion batteries (Airbus 2021).

Technical Considerations of Nuclear-Hydrogen Integrated Energy Systems

Hydrogen production is an ongoing topic of investigation in DOE's Light Water Reactor Sustainability program (Hallbert 2020). These research efforts have concluded that the most technically mature and cost-effective nuclear hydrogen production method is water electrolysis (either low or high temperature) (Boardman et al. 2019).[4] The main technology considered for low temperature electrolysis (LTE) is the PEM electrolyzer, while high-temperature steam electrolysis (HTSE) employs SOECs. Electrolyzers are both capital-intensive and energy intensive. LTE only requires electricity from the NPP while HTSE requires both electricity and heat and the system operates at temperatures of between 500°C and 1000°C. LTE does not require the system integration that HTSE entails, where diverting the thermal energy from the NPP necessitates more complicated engineering design and sometimes complex system integration. However, PEM electrolyzers rely on expensive catalysts to drive the hydrogen production process. Currently, the SOEC-based HTSE process sits at a lower level of technical readiness than PEM-based LTE processes. Hydrogen production with HTSE is more efficient (greater than 90 percent, versus 65 percent for LTE) however, leveraging its higher temperatures. If the technology becomes reliable, costs decline, and system integration issues are resolved, it is likely that the advantages of the HTSE process will encourage its deployment over LTE in integrated facilities using nuclear reactors.

Box 5-1 highlights a possible design for a nuclear-hydrogen system that uses existing light water reactors; it also outlines safety considerations for these facilities.

BOX 5-1
Design and Safety of an LWR/HTSE Plant and Hydrogen Production Process

One possible configuration for a nuclear-hydrogen integrated energy system (IES) involves an LWR, a thermal delivery loop, an HTSE hydrogen plant, and water and electricity supplies (Knighton et al. 2021). The hydrogen plant comprises of the SOEC stacks and the balance of plant components including high-temperature recuperators, topping heaters, a hydrogen purification system, and a multi-stage compression system. The process envisioned extracts a small portion of thermal power (5–10 percent) from an NPP at the inlet of the turbine and feeds that power to the HTSE plant through the thermal energy delivery loop consisting of an array of heat exchangers. Water and electricity are also fed into the HTSE hydrogen plant. The heat (~90 percent of the total thermal energy needed by the HTSE system to produce hydrogen) provided by the NPP is used to overcome the large amount of latent heat energy needed to vaporize large volumes of feedwater. Following vaporization of the feedwater, heat recuperation and topping heaters are used to supply the sensible heat needed to raise the steam up to HTSE operating temperatures (700°C–800°C), which accounts for the remaining 10 percent of the total thermal energy need for hydrogen production. The higher output temperatures (~700°C) of advanced nuclear reactors are advantageous, although the LWR heat (up to ~300°C) is also sufficient to vaporize water. The hydrogen purification system uses multiple stages to cool and compress the hydrogen stream to a temperature of 20°C, a pressure of 20 bar, and a purity of 99.9 percent (Wendt et al. 2022). However, a pressure of 20 bar is too low for economic hydrogen storage, transportation, or end-use applications such as FECV refueling stations; therefore, a multi-stage compression system is used to compress the purified hydrogen to approximately 70 bar, which is suitable for injection into a hydrogen distribution pipeline or a hydrogen storage system.

A key parameter in the design of an HTSE plant integrated with an NPP is the distance between the two, which has to be optimized to minimize heat loss, coolant pumping requirement, and capital costs, while ensuring the safe operation of the combined plant (IAEA 2013). The NRC has issued guidance to ensure that an explosion in the vicinity of a nuclear plant does not pose undue risk to the facility (see Box 7-1 below).[a] If a facility with potentially explosive materials is located closer to the nuclear plant than the computed minimum safety distance, it must be demonstrated that the rate of exposure to overpressure is less than 10^{-6} per year using conservative assumptions. This guidance

[4] Electrolysis of water is an electrochemical process to split water into hydrogen and oxygen gas using electricity.

was developed for conventional NPPs and has not been reevaluated to account for differences between conventional NPPs and advanced reactors, especially if designs forego containments.

[a] NRC, 2021, "Evaluation of Explosions Postulated to Occur at Nearby Facilities and on Transportation Routes near Nuclear Power Plants," Regulatory Guide 1.91, Revision 3, https://www.nrc.gov/docs/ML2126/ML21260A242.pdf.

Future advanced reactors are even better suited to integrate with HTSE-based hydrogen production from a technical standpoint. As discussed earlier, the HTSE process requires both electricity and heat. The combination of higher temperatures (above 500°C) and higher efficiency of electricity production from future advanced reactors will further improve the overall efficiency of HTSE-based hydrogen production compared to LWRs. Coupling advanced reactors with SOECs for hydrogen production initially will not be cost-competitive compared to LWRs because the capital cost of existing reactors has been recovered long ago. However, cost reductions in advanced reactors and performance improvement of the SOEC process may make this pathway competitive in comparison with other low-carbon hydrogen production pathways.

Another promising low-carbon hydrogen pathway enabled by advanced nuclear is via thermochemical splitting cycles, which only require heat from nuclear reactors and thus result in reduced integration effort and potentially overall cost reduction compared to the SOEC route. There are efforts to develop and learn from pilot-scale facilities that employ advanced nuclear reactors for hydrogen production through the sulfur-iodine (SI) process. For example, in 2019, the Japanese Atomic Energy Agency (JAEA) has successfully demonstrated continuous hydrogen production using its 30 MW(t) gas-cooled High Temperature Engineering Test Reactor (HTTR) through the SI process. In China, the Institute of Nuclear and New Energy Technology has also been planning to demonstrate coupling their HTR-10 (a high-temperature gas cooled reactor) with the SI plant for hydrogen production before 2025. (Suppiah 2020).

DOE Initiatives to Enable a Nuclear-Hydrogen Commercial Pathway

As the interest in hydrogen has grown again, so too have DOE's investments in projects that aim to increase the likelihood of successful commercialization of integrated energy systems that involve nuclear power. In recent years, DOE has awarded contracts to a few commercial nuclear utilities (Xcel Energy, Constellation Energy,[5] Energy Harbor, Arizona Public Service) to demonstrate the potential for nuclear plants to devote more of their operations to hydrogen production. The Xcel Energy project comprises, in Phase I, a techno-economic analysis of product diversification options that could help sustain the Monticello and Prairie Island NPPs in Minnesota (Knighton et al. 2021). Phase II will involve a demonstration that integrates a 150 kW HTSE with the Prairie Island nuclear plant. The initial hydrogen generation is expected to begin in 2024. Constellation Energy is seeking to demonstrate the integration of a 1.25 MW LTE with its Nine-Mile Point NPP in New York. This project has been ongoing since 2019 and is scheduled to produce hydrogen in 2023. Similarly, Energy Harbor is seeking to integrate a 2 MW LTE with its Davis-Besse nuclear power station in Ohio, with hydrogen production slated to commence in 2023 or 2024. In October 2021, Arizona Public Service received an award for a hydrogen demonstration project at the Palo Verde NPP. This project is still in contract negotiation stage and if successful, it would start producing hydrogen as early as 2024 through the integration of a 15–20 MW LTE. These pilot-scale nuclear plus hydrogen systems revolve around demonstrating flexible plant operations during times of peak wind or solar generation, enabling their dynamic participation in an organized electricity market, or for clean hydrogen production to be used for local public transportation or

[5] The contract was originally awarded to Exelon Corporation. Following the reorganization of its nuclear plants from Exelon Corporation in 2022, the project is now carried out by Constellation Energy.

local industrial customers. These demonstrations will employ a system design that can be scaled up and used for other hydrogen production applications and could meet regulatory requirements (Vedros et al. 2020).

These demonstrations will enable much better understanding of the interface between the NPP and the electrolyzers, how plant operations unfold in practice, and how to manage the storage and transport of hydrogen. More importantly, they will enable a more comprehensive understanding of the regulatory, financial, and safety issues surrounding such concepts. These lessons could be used to scale up hydrogen production via NPPs and ensure that vendors of advanced nuclear reactors understand what these integrated systems require in the real world.

Augmenting these developments, DOE launched its "Hydrogen Shot" in June 2021,[6] an initiative aimed at reducing the cost of clean hydrogen production by 80 percent to $1 per 1 kilogram in 1 decade ("1 1 1"). The 2021 Infrastructure Investment and Jobs Act (IIJA) earmarked about $8 billion to establish at least 4 regional clean hydrogen hubs to improve clean hydrogen production technologies from production to processing, delivery, storage, and end use. These hubs will pursue several technology pathways to achieve this ambitious goal and enable the widespread use of hydrogen as a clean fuel and chemical feedstock. The IIJA mandates that one hydrogen hub shall be dedicated to nuclear generation resources, which reaffirms DOE's support for nuclear-hydrogen commercialization pathways. More recently, the IRA has established a clean hydrogen tax credit, that ranges from 1.2 to 60 cent per kilogram, depending on the carbon intensity of the hydrogen production pathway that is employed. Significantly, this credit is stackable, meaning that it could be used in conjunction with other credits: for example, on top of a tax credit for the use of low-carbon electricity to produce the hydrogen (IRA 2022).

Understanding the Cost of Low-Carbon Hydrogen Production Pathways

To achieve DOE's "1 1 1" goal, it is important to understand the cost of hydrogen production for various low-carbon technologies. The $1 per kg-$H_2$ goal refers to the levelized cost of hydrogen (LCOH), which is used to account for all the capital and operating costs of producing hydrogen and to indicate how much it costs to produce 1 kg of hydrogen over the assumed lifetime of the hydrogen production plant. LCOH allows different production pathways to be compared on a similar basis and is determined by the capital cost of energy supply, the capacitor factor of energy supply (90 percent for nuclear versus 20 percent for solar), among others. Factors unique to the LCOH of electrolytic hydrogen production pathway include the hydrogen plant capital cost, the efficiency of electrolyzers, and so on.

When it comes to the nuclear-hydrogen route, it is likely that the goal set by the Hydrogen Shot initiative can only be realized by the existing fleet of nuclear reactors, rather than one of the advanced reactors. This is because existing LWRs operate at high-capacity factors and have already recovered their costs; the electricity they produce is relatively cheap, and they already exist. Analyses have shown that it costs $1.93 (in 2020 dollars)[7] to produce 1 kg of hydrogen for an integrated LWR/HTSE plant starting operations in year 2027 and there is a pathway to achieve the goal of $1 per kg-$H_2$ (Knighton et al. 2021). Nuclear-generated hydrogen could be made cost-competitive with steam methane reforming by 2030, as costs decline, performance improves, and carbon emission restrictions are enforced. In fact, it is crucial for electrolytic hydrogen production to be cost competitive with the incumbent technology, steam methane reforming retrofitted with carbon capture, utilization, and storage (CCUS), within a decade or so, for it to be widely adopted to play a meaningful role in deep decarbonization. The LCOH for the steam methane reforming technology before the recent high natural gas price scenario was on average as low as $1 per kg-$H_2$. Because this technology is tied to natural gas prices, its cost can be volatile, as witnessed in certain regions of the world in 2022. In a recent Nuclear Energy Agency ("NEA") study, the LCOH for steam methane reforming with CCUS in the year 2035 is estimated to be between $2 per kg-$H_2$ and $5.87

[6] Hydrogen Shot is part of the DOE Energy Earthshots Initiative and was the first Earthshot to launch.

[7] This is estimated for a nth-of-a-kind LWR/HTSE plant approximately 4–5 years in the future when a 95 percent learning curve and at-scale SOEC supplies can be assumed.

per kg-H_2, bounded by a low natural gas price of $20 per MWh (or ~6 $/MMBTU) and a high natural gas price of $100 per MWh (or ~30 $/MMBTU). With the natural gas price in 2022 at approximately $45/MWh, which is still below the prices in certain regions of the world in 2022, steam methane reforming with CCUS is the least affordable option compared to nuclear or renewable pathways (NEA 2022). Deployment of steam methane reforming with CCUS is also geographically limited given the geologic constraints for CO_2 sequestration.

Renewables and nuclear are two major clean energy resources considered in the electrolytic hydrogen pathways. There is a consensus among industry that PEM and SOEC will be the main electrolyzer technologies replied on to scale up renewable and nuclear-based hydrogen production in the next two to three decades (NEA 2022; Ingersoll and Gogan 2020). Breaking down the LCOH of electrolytic pathways is key to understand how the nuclear option compares to renewables.

The LCOH of electrolytic technologies is composed of the levelized cost of energy and the levelized cost of the electrolyzer. The levelized cost of electricity, as a major part of the levelized cost of energy, stands out as the single most important factor in influencing LCOH for all options. Electricity price from depreciated LWRs and the cheapest renewable resources, such as solar in Middle East and North America, are much more competitive than other low-carbon resources, such as solar in Europe or offshore wind. The levelized cost of the electrolyzer consists of both capital cost and operating cost, which are heavily affected by three factors: the cost and performance of the hydrogen plant itself, the capacity factor of the energy source, and the efficiency of the electrolyzer. The engineering and capital costs for SOEC plants are more than those of PEM plants. Currently, PEM plants have a longer lifespan and lower degradation rate compared to SOECs. However, these are just part of the picture in determining the levelized cost of electrolyzers. A high-capacity factor of the energy source powering the hydrogen plant can lead to a better utilization of the electrolyzer and thus a positive impact in the overall levelized cost of hydrogen. For example, it has been shown that with other factors held constant, the LCOH triples when moving from a 90 percent capacitor capacity factor electric source (e.g., nuclear) to 20 percent capacity factor (e.g., solar) (Ingersoll and Gogan 2020). Last, the efficiency of the electrolyzer also plays a role in the levelized cost. By using some thermal energy (less than 10 percent of the overall energy required), SOEC uses less electricity than PEM and can achieve hydrogen production at above 95 percent efficiency. This is a very important aspect as it provides a favorable prospect for the nuclear electrolytic hydrogen pathway. Moreover, because renewables cannot provide heat (at least not directly or efficiently), it makes sense to use nuclear power (both existing fleet and future advanced reactors) to integrate with SOECs.

In conclusion, the factors that affect electrolytic hydrogen LCOH are complex and interrelated. Renewables may be able to provide the cheaper electricity in certain scenarios compared to nuclear power but suffer lower capacity factors in general and do not have the SOEC integration option. As such, most studies show that renewable hydrogen LCOH is higher than that of depreciated LWRs for both the current scenario and the year 2030. According to Bloomberg New Energy Finance (BNEF), the current cost of renewable-driven electrolytic hydrogen production is above $4 per kg-$H_2$ (BNEF 2020). In year 2030, the best-case wind and solar will produce hydrogen at $2–$3 per kg-H_2 using cost projections from NREL (Ingersoll and Gogan 2020). Besides cost constraints, the renewable-hydrogen pathway also faces other constraints at the scale required to match the global hydrogen demand, such as land constraints and the associated ecological as well as social and political concerns related to “energy sprawl.” Regional resources endowment (e.g., access to large amounts of cheap electricity, low natural gas prices) will likely play a role in determining the cost of hydrogen production and the future clean hydrogen technology landscape.

The LWR/HTSE pathway has strong potential to reach the $1 per kg-$H_2$ goal in one decade. At the moment, not only are these stacks expensive (SOEC stack capital costs are currently at $155/kW-dc), but also, they are relatively short-lived (SOEC stacks have a service life of 4 years, after which their production capacity falls to 67 percent, eventually necessitating capital outlays for replacement) (Peterson et al. 2020). However, some analyses project that a cost of $27/kW-dc could be achieved by 2030 as large-scale SOEC manufacturing capacity continues to expand in the coming years (Tang et al. 2018), and that the stack degradation rates might be halved in the next few years. Lower SOEC degradation rates impact both its service life and replacement schedule, ultimately contributing to lower costs. For the nuclear-hydrogen pathway to be cost competitive in general, the costs of both nuclear reactors and electrolytic cells must fall drastically. If new and advanced reactors are commercialized in the coming decades, their availability might coincide with that of cheaper, better performing SOEC stacks, improving the economic viability of the plant. Some transformative manufacturing methods such as a hydrogen gigafactory or existing world-class shipyards have been proposed that might significantly reduce the cost of future advanced reactors as well as hydrogen production to \$0.9 per kg-H_2 by 2030 (Ingersoll and Gogan 2020; EPRI 2021b).

LCOH is a key indicator for investors and policymakers who seek to choose among different options for hydrogen production. However, LCOH applies at the individual production unit level and thus only tells part of the story. For example, co-locating hydrogen production with cheap electricity resources may reduce the cost of hydrogen production itself but may lead to substantial costs for the hydrogen delivery system to a customer. A comprehensive analysis of the economic costs of various hydrogen production options needs to consider the costs across the entire value chain, including those associated with hydrogen storage, transportation, and distribution. A recent NEA analysis argues that nuclear energy could help sustain a competitive hydrogen production pathway (NEA 2022). This analysis shows that a mismatch in hydrogen production and consumption profiles is likely to cause inefficient infrastructure design. In the short term, most of the demand will likely come from industry, which requires a steady flow of hydrogen. For meeting the unremitting industrial demand, the low-capacity factor associated with renewable-powered hydrogen production facilities would likely require over-sizing the infrastructure, including hydrogen storage and transportation and distribution systems, reducing the competitiveness of this pathway. As an energy source with a high-capacity factor, nuclear power would enhance co-location synergies with large-scale industry demand, minimizing infrastructure costs for hydrogen storage, transportation, and distribution.

The hydrogen value chains are likely to be designed on a case-by-case basis, and this complexity renders evaluating the cost of hydrogen delivery a serious challenge. Nonetheless, such assessments are valuable because frequently, the total cost of value chain will determine the competitiveness of different business models for hydrogen production.

One additional complexity arises from proposals to coproduce electricity with production of a non-electricity product. For example, the vision of an advanced NPP serving the electric grid when necessary and then switching to hydrogen production when electric power supply exceeds demand, requires the reactor operator to incur substantial capital investments in the engineering systems, infrastructure, and regulatory compliance that is necessary for frequent switching between the two services. If clean hydrogen commands a premium—as it is likely to—a reactor operator might well choose instead to design a plant that is dedicated to its production, perhaps even if that entails investment in hydrogen storage in order to exploit its higher revenue stream. In such a case, a reactor operator might only resort to selling electric power if the market operator or another regulatory body demands that it does so, either in the form of a hard constraint or a substantial economic incentive. Clearly, calculating the levelized cost of the different products for such "hybrid" operational paradigms is highly site-specific, dependent as it is on the power system in which the reactor operates, the regulatory context, and other factors. Without certainty in how the electricity and energy markets are likely to evolve, investing in the infrastructure necessary to exploit hybrid operations incurs an economic and regulatory risk.

Hydrogen-Based Liquid Fuels Enabling Long-Distance Transportation Decarbonization

Without significant investments, economies will continue to rely heavily on liquid hydrocarbon fuels to power the transportation sector (from surface transportation to aviation to marine shipping). Battery electric vehicles will play a significant role in replacing conventional internal combustion engine vehicles, but heavy-duty freight, aviation, and ocean shipping require vastly greater energy densities than batteries can offer. Liquid hydrogen, despite its high gravimetric energy density, has a lower volumetric energy density[8] than liquid hydrocarbon fuels. The liquefaction of hydrogen is also energy intensive: it requires high pressures and cryogenic temperatures of < –253°C for storage.

Chemical compounding—combining hydrogen into other, denser molecules—offers a solution to address some of the difficulties associated with liquid hydrogen. Liquid fuels such as ammonia and synthetic hydrocarbons have the potential to solve both the energy density and fuel distribution challenges that face liquid hydrogen.

Ammonia is produced using the century-old Haber-Bosch process, where hydrogen and nitrogen are reacted at high temperatures and pressures. Ammonia can remain in liquid form at near atmospheric pressure and at temperatures of < –33.34°C, making it easier to store and transport than liquid hydrogen. In addition, liquid ammonia is approximately 1.5 times as energy dense as liquid hydrogen. These attributes mean that ammonia lends itself for use in ocean shipping and remote, off-grid applications. For example, minor modifications are required for some existing ship engines to combust ammonia and building a distribution network is easier for ammonia than it is for liquid hydrogen. There are significant concerns regarding ammonia's toxicity and nitrous oxide and NOx formation upon combustion or as a result of leakage NOx-reduction technologies are widely available and intensive capacity building to ensure that fuel handling meets high safety standards.

The Haber-Bosch based ammonia synthesis process is energy intensive: it operates at temperatures between 400°C and 500°C and at pressures of up to approximately 200 bar. Nuclear power could be a primary low-carbon energy source for ammonia production. For example, both the nuclear heat and electricity could produce hydrogen using the HTSE process. The hydrogen and nitrogen could then be fed into an ammonia synthesis plant, powered by nuclear electricity. Because the ammonia synthesis process is exothermic, the heat produced in ammonia production can be recycled back to the hydrogen plant to supplement the high thermal energy requirements of the SOEC stacks.

Synthetic liquid hydrocarbons offer another important opportunity to decarbonize parts of the transportation sector that are difficult to electrify. Synthetic liquid hydrocarbons, also commonly referred to as drop-in fuels, are chemically identical to the distillates that are derived from petroleum (e.g., gasoline, diesel, or jet fuel). These substitute fuels could leverage well-established fuel storage and transportation systems and standards, not to mention the utilization of the existing fossil fuel infrastructure. For synthetic liquid hydrocarbons to be carbon neutral, they must be produced from CO_2 that is already in the atmosphere—direct air capture of carbon dioxide is an area of growing interest and investment—and the additional inputs to the manufacturing process (e.g., electricity, hydrogen) must also be emission-free.[9]

There are several pathways to produce syngas (a mix of carbon monoxide and hydrogen) using CO_2 as a feedstock, employing clean energy resources such as nuclear to eliminate the emissions associated with the synthetic liquid fuel manufacturing process. One such possibility is co-electrolysis. In co-electrolysis, CO_2 is reacted with water in a SOEC system to produce syngas, which can be subsequently converted to transportation fuels through the Fischer-Tropsch or Mobil processes.

One of the main obstacles to electrolytic ammonia and synthetic hydrocarbons is the cost and performance of the SOECs themselves, as discussed previously. Like advanced nuclear reactors, these components will need to demonstrate that they are economically competitive, durable, and reliable. The other components required to make the CO_2-to-fuel supply chain a reality are complex and capital-intensive, but technologically mature. They include Fischer-Tropsch reactors and a combination of distillation, upgrading, cracking, and reforming units—units that have been employed in the petroleum refining industry in some cases for a century. The same can be said for ammonia synthesis process itself, which is a very proven technology. Even if the performance of SOECs improves—ongoing research is

[8] In this chapter, energy density and volumetric energy density are used interchangeably; they refer to the amount of energy stored in a given system or region of space per unit volume.

[9] Currently, synthetic liquid hydrocarbons are predominantly produced using feedstocks and energy derived from fossil fuels, and generate net CO_2 emissions. Refer to Table 5-2 for the conventional synthetic fuel process.

making great strides in this field (Hauch et al. 2020)—these integrated systems to produce low-carbon ammonia and synthetic hydrocarbons will require large amounts of emissions-free electricity and heat to run the combined electrochemical and thermochemical synthesis processes: small nuclear reactors could conceivably provide that energy.

Other Process Heat Applications

Many industrial facilities rely on thermochemical processes—chemical processes that employ heat to distill, separate, desorb, or otherwise recover specific substances. The temperatures required depend on specific chemical processes (see Figure 5-2 above, and Box 5-2 below). Because nuclear reactors provide heat, the chemical industry has interest in potentially acquiring reactors as carbon constraints tighten, or fossil fuel supplies dwindle or become expensive. Ongoing concerns regarding climate change have revivified this interest (Nuclear Newswire 2022; Goetzke et al. 2022). A recent study employed 6 years of steam demand data to explore how four generic nuclear reactor options (small modular light water reactor, high-temperature gas reactor, liquid metal fast reactor, and fluoride-salt cooled reactor) might serve Eastman Chemical's Kingsport facility, which produces specialty chemicals (Greenwood et al. 2020). It evaluated their ability to meet Eastman's demand, the operational reliability of their steam and electric supply, and their potential costs compared to status quo, natural gas fired supply. While drawing no specific conclusions, the report indicated that an SMR could potentially meet the existing process heat needs of the Kingsport facility but noted that the required capital investment would be substantial and present a major hurdle. Efforts to electrify thermochemical processes could reduce the need for siting nuclear reactors near industrial facilities, although the reactors would have to compete with other sources of low-carbon electricity and heat, such as natural gas with carbon capture and storage.

Other possible industrial integrations include using nuclear power for running a cryogenic refrigerant cycle, the chlor-alkali process, and formic acid production. A cryogenic refrigerant cycle could be powered by NPPs when the electricity price is low or there is grid over-generation. The cryogenic refrigerant can be regarded as a form of energy storage and can be used onsite as needed or transported short distances to the point of use.

Chlor-alkali electrolysis plants show strong technical potential for integration with an NPP from both heat and electricity-demand perspectives. The chlor-alkali process electrochemically converts NaCl-rich brine (i.e., sodium chloride solutions) into chlorine gas and sodium hydroxide (i.e., NaOH or caustic soda), both of which are commodity chemicals commonly required by industry. For example, chlorine is used for producing polyvinyl chloride (PVC), water treatment, pharmaceuticals, and other chemicals. NaOH is widely employed in industrial process to manufacture soaps, paper, dyes, petroleum products, and so on. The chlor-alkali industry is projected to grow in the next decade with possibility to use a low-carbon energy source such as nuclear power to reduce CO_2 emissions.[10]

Formic acid can be produced by co-electrolysis of CO_2 and water using the electricity and possibly heat from NPPs (Lu et al. 2014). Formic acid is relatively nontoxic and allows easy long-term storage. Currently, formic acid is used to produce natural and synthetic leathers, textiles, cleaning products, and rubber. Formic acid has been widely used abroad as an antimicrobial additive in animal feed, an application of increasing interest in the United States as the use of antibiotics in farming has been under increasing scrutiny (Tullo 2015). In addition to its traditional uses, formic acid could serve as an energy-dense hydrogen carrier that is liquid at ambient conditions (BMT 2009; Yang et al. 2017). One manufacturer, OCO Chemicals, has reported that its licensed process boasts a 78 percent efficiency with a high selectivity of 99 percent in reducing CO2 to formic acid or formate salts (OCO Chemicals 2021).

The domestic and global demand for formic acid is projected to grow (Transparency Market Research 2018). Low-carbon baseload nuclear power is well suited to provide the energy to decarbonize the formic acid production process. In addition to energy costs, other key cost drivers to make formic acid

[10] Currently the chlor-alkali process accounts for 4 percent of total industrial CO_2 emissions.

cheaper than alternative chemicals are the performance and cost of co-electrolysis cells, which can reduce both capital and operating costs, as well as the feedstock price of CO_2.

> Finding 5-2: Process heat applications exist at a variety of temperature ranges. Higher-temperature applications are likely going to be more difficult to electrify, because there are fewer available low-carbon heat options. Reactor systems with higher outlet temperatures could conceivably serve processes requiring temperatures between 300°C and 800°C. These reactors would need to demonstrate a high degree of safety with minimal reactivity feedbacks between the reactor and the process heat application. These are necessary attributes for siting a nuclear plant near a facility for industrial heat applications.

BOX 5-2
Reinventing Industrial Processes to Not Use Heat

Discussions of industrial decarbonization generally assume that, in a net-zero world, the sector will need to find low-carbon energy sources, rather than reconfigure its thermochemical processes in a radical way so that they do not use heat. This assumption is plausible and valid in the near-term, but, in the longer term, industry could also seek to transition from a thermochemical paradigm to an electrochemical one, which would entail substantial investments in redesigning industrial processes, scaling them up for global deployment, and servicing them with large amounts of low-carbon electric power and smaller amounts of heat. Electrified commercialized options exist in some industries (e.g., steel), but not most.

District Heating

District heating systems have been used to provide heating to networks of buildings across the world for the past 150 years. More than 900 installations in the United States and Canada use such systems, in some cases coupling them with steam-turbine-driven chillers to provide district cooling as well. These applications use heat produced at the relatively low temperatures that LWRs could provide (<125°C). Several existing NPPs supply such heat via hot water or low-pressure steam (IAEA 2003; Leppanen 2019) and are connected to municipal heat distribution systems to provide district heating services. The typical system extracts non-radioactive steam from the secondary circuit of the LWR, which is then fed to an on-site heat exchange station connected to a separate water loop. This heat is then fed to an off-site heat exchange station, which allows hot water to flow through municipal heating pipes to consumers.

China has been exploring the use of small nuclear reactors as alternative heating systems in smog-prone regions, thereby avoiding the use of coal- or gas-fired boilers (Zhang et al. 2017). Recently, the Haiyang NPP (an AP1000 LWR) in Shandong province has started providing district heat to the surrounding area. A trial of the project—the country’s first commercial nuclear heating project—was carried out in winter 2019, providing heat to 700,000 square meters of housing, including the plant and local residents (World Nuclear News 2020a). As of late 2021, the Haiyang system is providing district heating to the entire city of Haiyang, a city of approximately 200,000 (Kraev 2021). Additionally, Finland is studying the use of a set of small nuclear reactors for district heating (World Nuclear News 2020b).

While the cost and technology readiness for district heat provided by nuclear energy are promising, major issues would need to be addressed for it to play a role in the future U.S. energy system, including increased commitments to district heating (which itself requires substantial investments in laying the necessary infrastructure), greater public acceptance of nuclear plant sites in relative proximity to populated centers, and the regulatory issues associated with siting reactors that serve hybrid electric-thermal or thermal needs.

Water Desalination

Desalinated water is an essential commodity in arid regions of the world that have limited access to freshwater resources, such as the Middle East. Desalination can be achieved through any one of several proven technologies, such as reverse osmosis, which uses only electricity, or a variety of low temperature (75°C) heat-based processes that use distillation (Shatilla 2020). The current global market for desalinated water is relatively modest (Grand View Research 2022); however, water pollution, urbanization, and water scarcity are issues that could increase the market for desalinated water by the time advanced nuclear reactors begin to come online. The Middle East and North Africa have the greatest potential market for desalinated water owing to growing populations and existing water scarcity issues (Ahn et al. 2021).

As shown in Figure 5-3, nuclear desalination plants today produce between 1,000 and 160,000 m^3 of water per day. Two issues limit the likelihood of expanded deployment of nuclear power for water desalination. The first, highlighted throughout this report, is cost. A recent study (Rath 2020) compared hybrid systems that employ either SMRs or natural gas with carbon capture and storage to desalinate water. It found that the cost of carbon emissions would have to rise to $200/t$CO_2$ for the SMR solution to clearly dominate the natural gas option. The second issue is water pricing: even in water-scarce regions, water is severely underpriced. Absent a change in policy governing the pricing of either water or carbon, this means that, outside of a very small subset of locations, like the Monterrey Peninsula or the Middle East, this market is unlikely to expand to a level that would enable the mass deployment of nuclear power, although any location that employs SMRs for other reasons could certainly opt to integrate water desalination into its plans.

A 2019 review of the literature found the cost of water production using nuclear desalination was estimated to range from $0.4/$m^3$ to $1.8/$m^3$ depending on the type of reactor and the desalination process used (Al-Othman et al. 2019). The World Nuclear Association reports the cost of water production using nuclear desalination to be similar to fossil-fueled plants today, around $0.7/$m^3$ to $0.9/$m^3$ (WNA 2020). A study of California's Diablo Canyon nuclear reactor found that if the reactor were reoriented around coordinated electricity generation, hydrogen production, and desalination, water would cost $0.79/$m^3$ to $0.98/$m^3$ (Aborn et al. 2021; see Table 5-3). Using Diablo Canyon as a power source for desalination could substantially augment fresh water supplies to the state as a whole and relieve withdrawal from critically over drafted basins regions such as the Central Valley, producing freshwater volumes equal to or substantially exceeding those of the proposed Delta Conveyance Project, but at significantly lower investment cost.

> Finding 5-3: Several proposed non-electric services, such as low-temperature heat and desalination, currently cost very little and likely would not be compensated at a level that encourages new nuclear deployment. Hydrogen provides perhaps the most credible non-electric revenue stream for nuclear reactors, because it is likely that hydrogen will have value across the industrial, power, and transportation sectors for deep decarbonization.

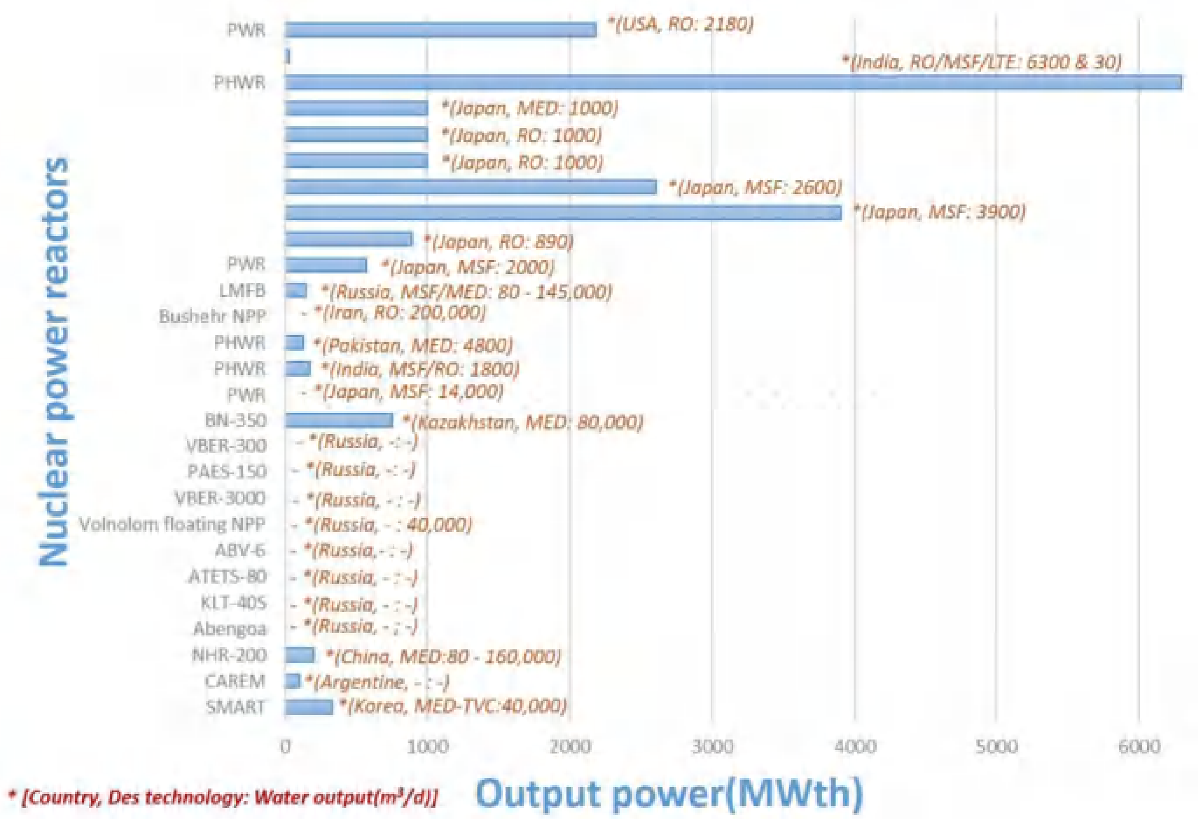

FIGURE 5-3 Current status of all types of nuclear desalination plants, with power output, desalination technology used, water ratio, and country of origin.
SOURCE: S.U. Khan and J. Orfi, 2021, "Socio-Economic and Environmental Impact of Nuclear Desalination," *Water* 13(12):1637, https://doi.org/10.3390/w13121637. CC BY 4.0.

TABLE 5-3 Key Results from Technoeconomic Analysis of Two Proposed Combined Hydrogen, Desalination, and Electricity Generation Projects at Diablo Canyon Compared to the Estimates for the Carlsbad Desalination Plant[a]

		Large Scale at Diablo	**Mega Scale at Diablo**	**Carlsbad Estimated**
Capacity (m^3/d)		189,270	4,752,000	189,270
Total Capex ($ million)		599	11,571	1,235
Energy consumption (kWh/m^3)		3.5	3.5	3.5
Electricity price ($/kWh)		$0.054	$0.054	$0.139
Water cost breakdown ($/$m^3$)	Capital costs and amortization	$0.53	$0.41	$1.10
	Operating costs (excluding energy)	$0.26	$0.19	$0.26
	Energy costs	$0.19	$0.19	$0.49
	Water price at plant outlet ($/$m^3$)	$0.98	$0.79	$1.84

[a] The Claude "Bud" Lewis Carlsbad Desalination Plant is a desalination plant that opened on December 14, 2015, in Carlsbad, California, north of the Encina Power Station. Its output constitutes approximately 7 percent of the water supply for San Diego County.
SOURCE: Committee generated with data from J. Aborn, E. Baik, S. Benson, et al., 2021. *An Assessment of the Diablo Canyon Nuclear Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Productions*, Stanford University Precourt Institute of Energy, https://drive.google.com/file/d/1RcWmKwqgzvIgllh0BB2s5cA6ajuVJJzt/view.

REFERENCES

Aborn, J., E. Baik, S. Benson, A.T. Bouma, J. Buongiorno, J.H. Lienhard, J. Parsons, and Q.J. Wei. 2021. *An Assessment of the Diablo Canyon Nuclear Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Production*. Stanford University Precourt Institute of Energy. https://energy.stanford.edu/publications/assessment-diablo-canyon-nuclear-plant-zero-carbon-electricity-desalination-and.

Accenture. 2021. "Industrial Clusters: Working Together to Achieve Net Zero." https://www.accenture.com/_acnmedia/PDF-147/Accenture-WEF-Industrial-Clusters-Report.pdf#zoom=40.

Ahn, A., J. Kincer, T. Moss, J. Freed, and J. Lovering. 2021. "2021 Update: Map of the Global Market for Advanced Nuclear." http://thirdway.imgix.net/pdfs/2021-update-map-of-the-global-market-for-advanced-nuclear.pdf.

Al-Othman, A., N.N. Darwish, M. Qasim, M. Tawalbeh, N.A. Darwish, and N. Hilal. 2019. "Nuclear Desalination: A State-of-the-Art Review." *Desalination* 457(May):39–61. https://doi.org/10.1016/j.desal.2019.01.002.

Bloomberg New Energy Finance. 2020. *Hydrogen Economy Outlook: Key Messages*. Bloomberg Finance LP.

BMT. 2009. "Formic Acid." https://cargohandbook.com/index.php/Formic_acid.

Boardman, R.D., C. Rabiti, S.G. Hancock, D.S. Wendt, K.L. Frick, S.M. Bragg-Sitton, H. Hu, et al. 2019. *Evaluation of Non-Electric Market Options for a Light-Water Reactor in the Midwest. Light Water Reactor Sustainability Program*. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1559965.

Buongiorno, J., M. Corradini, J. Parsons, and D. Petti. 2018. *The Future of Nuclear Energy in a Carbon-Constrained World*. Cambridge, MA: Massachusetts Institute of Technology Energy Initiative.

Demick, L. 2010. *High Temperature Gas-Cooled Reactor Projected Markets and Scoping Economics*. INL/EXT-10-19037. Idaho Falls, ID: Idaho national Laboratory. https://doi.org/10.2172/989904.

DOE (Department of Energy). 2020. *The U.S. Department of Energy Hydrogen Program Plan*. DOE/EE-2128. Washington, DC: Department of Energy.

EIA (Energy Information Administration). 2021. *Monthly Energy Review*. DOE/EIA-0035. Table 1.3 and Table 10.1. Washington, DC: Department of Energy.

EPRI (Electric Power Research Institute). 2014. *Program on Technology Innovation: Approach to Transition Nuclear Power Plants to Flexible Power Operations*. 3002002612. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2017. *Program on Technology Innovation: Expanding the Concept of Flexibility for Advanced Reactors: Refined Criteria, a Proposed Technology Readiness Scale, and Time- Dependent Technical Information Availability: Refined Criteria, a Proposed Technology Readiness Scale, and Time-Dependent Technical Information Availability*. 3002010479. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2019. *Program on Technology Innovation: Owner-Operator Requirements Guide (ORG) for Advanced Reactors, Revision 1*. 3002015751. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2020. *Technology Innovation Prospectus 2020–21: Pathways to a Decarbonized Future*. 3002019513. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2021a. *Nuclear Beyond Electricity—Motivating and Valuing the Flexibility of Nuclear Energy Systems*. 3002020436. Palo Alto, CA: Electric Power Research Institute.

EPRI. 2021b. *Rethinking Deployment of Scenarios to Enable Large-Scale, Demand-Driven Non-Electricity Markets for Advanced Reactors*. 3002022311. Palo Alto, CA: Electric Power Research Institute.

European Commission. 2020. *A Hydrogen Strategy for a Climate-Neutral Europe.* COM(2020)301 final. European Commission, Brussels. https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.
FCH JU (Fuel Cells and Hydrogen 2 Joint Undertaking). 2019. *Hydrogen Roadmap Europe: A Sustainable Pathway for the European Energy Transition*. https://data.europa.eu/doi/10.2843/341510.
Glover A., A Bard, D. Brooks. 2020. *Final Report on Hydrogen Plant Hazards and Risk Analysis Supporting Hydrogen Plant Siting Near Nuclear Power Plants*. SAND2020-7946. Albuquerque, New Mexico: Sandia National Laboratories.
Goetzke, R., I. Garza, M. Nena, R. Field, S. Malak, and A. Wilson. 2022. *The Viability of Nuclear Plant Process Heat for Industrial Usage*. Chicago, IL: Sargent & Lundy.
Grand View Research. 2022. *Water Desalination Equipment Market Size, Share and Trends Analysis Report by Technology, by Source, by Application, by Region, and Segment Forecasts, 2023–2030.* GVR-1-68038-489-5. https://www.grandviewresearch.com/industry-analysis/water-desalination-equipment-market.
Greenwood, M.S., A.G. Yigitoglu, J.D. Rader, W. Tharp, M. Poore, et al. 2020. *Integrated Energy System Investigation for the Eastman Chemical Company, Kingsport, TN Facility*. Oak Ridge, TN: Oak Ridge National Laboratory. https://doi.org/10.2172/1643929.
Hallbert, B. 2020. *Light Water Reactor Sustainability 2019 Accomplishments Report*. Washington, DC: Department of Energy.
Hauch, A., R. Küngas, P. Blennow, A.B. Hansen, J.B. Hansen, B.V. Mathiesen, and M.B. Mogensen. 2020. "Recent Advances in Solid Oxide Cell Technology for Electrolysis." *Science* 370(6513):eaba6118. https://doi.org/10.1126/science.aba6118.
Heinemann, N., J. Alcalde, J.M. Miocic, S.J.T. Hangx, J. Kallmeyer, C. Ostertag-Henning, et al. 2021. "Enabling Large-Scale Hydrogen Storage in Porous Media—the Scientific Challenges." *Energy and Environmental Science* 14(2):853–864. https://doi.org/10.1039/D0EE03536J.
IAEA (International Atomic Energy Agency). 2003. *Market Potential for Non-Electric Applications of Nuclear Energy.* Technical Reports Series 410. Vienna: International Atomic Energy Agency.
IAEA. 2013. *Hydrogen Production Using Nuclear Energy*. IAEA Nuclear Energy Series No. NP-T-4.2. Vienna: International Atomic Energy Agency.
IAEA. 2018. *Non-Baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation*. IAEA Nuclear Energy Series No. NP-T03.23. Vienna: International Atomic Energy Agency.
IEA (International Energy Agency). 2019. *The Future of Hydrogen: Seizing Today's Opportunities*. Paris: International Energy Agency.
IEA. 2021a. *World Energy Outlook 2021*. Paris: International Energy Agency.
IEA. 2021b. *Net Zero by 2050*. Paris: International Energy Agency.
Ingersoll, E., and K. Gogan. 2020. *Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals*. LucidCatalyst.
Khan, S.U., and J. Orfi. 2021. "Socio-Economic and Environmental Impact of Nuclear Desalination." *Water* 13(12):1637. https://doi.org/10.3390/w13121637.
Knighton, L., D. Wendt, J. Richards, C. Rabiti, A.A. Jaoude, T. Westover, K. Vedros, et al. 2021. *Techno-Economic Analysis of Product Diversification Options for Sustainability of the Monticello and Prairie Island Nuclear Power Plants*. INL/EXT-21-62563-Rev001. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1843030.
Kraev, K. 2021. "China/City of Haiyang 'First in Country' to Have District Heating System Powered by Nuclear." *NucNet Plant Operation*, November 12. https://www.nucnet.org/news/city-of-haiyang-first-in-country-to-have-district-heating-system-powered-by-nuclear-11-5-2021.
Leppanen, J. 2019. *A Review of District Heating Reactor Technology*. VTT-R-06895-18. VTT Technical Research Centre of Finland. https://cris.vtt.fi/ws/portalfiles/portal/24936486/VTT_R_06895_18.pdf.
Lu, X., D.Y.C. Leung, H. Wang, M.K.H. Leung, and J. Xuan. 2014. "Electrochemical Reduction of Carbon Dioxide to Formic Acid." *ChemElectroChem* 1:836–849. https://doi.org/10.1002/celc.201300206.

NRCan (Natural Resources Canada). 2020. *Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen*. No. M134-65/2020E-PDF. Ottawa: Natural Resources Canada.
Nuclear Newswire. 2022. "X-Energy, DOW to Collaborate on SMR Deployment." *Nuclear Newswire*, August 9. https://www.ans.org/news/article-4212/xenergy-dow-to-collaborate-on-smr-deployment.
OCO Chemicals. 2021. "Technology." https://ocochem.com/technology.
OECD-NEA (Organisation for Economic Co-Operation and Development-Nuclear Energy Agency). 2011. *Technical and Economic Aspects of Load Following with Nuclear Power Plants*. Organisation for Economic Co-Operation and Development.
OECD-NEA. 2022. *The Role of Nuclear Power in the Hydrogen Economy: Cost and Competitiveness*. NEA No. 7630. Organisation for Economic Co-Operation and Development.
Peterson, D., J. Vickers, and D. DeSantis. 2020. *Hydrogen Production Cost from High Temperature Electrolysis—2020*. Report #20006. Washington, DC: Department of Energy.
Scita, R., P.P. Raimondi, and M. Noussan. 2020. "Previous Waves of Enthusiasm for Hydrogen:" Pp. 5–7 in *Green Hydrogen: The Holy Grail of Decarbonization? An Analysis of the Technical and Geopolitical Implications of the Future Hydrogen Economy*, M. Hafner, ed. Fondazione Eni Enrico Mattei: JSTOR. http://www.jstor.org/stable/resrep26335.4.
Shatilla, Y. 2020. "7. Nuclear Desalination." Pp. 247–70 in *Nuclear Reactor Technology Development and Utilization*, S. Ud-Din Khan and A. Nakhabov, eds. Woodhead Publishing. https://doi.org/10.1016/B978-0-12-818483-7.00007-X.
Siirola, J. 2021. "Nuclear and the Chemical Industries." Presented to the National Academies' Committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States, July 20. https://www.nationalacademies.org/event/07-19-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-6.
Transparency Market Research. 2018. "Formic Acid Market—Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2017–2025." https://www.transparencymarketresearch.com/formic-acid-market.html.
Tseng, P., J. Lee, and P. Friley. 2005. "A Hydrogen Economy: Opportunities and Challenges." *Energy* 30(14):2703–2720. https://doi.org/10.1016/j.energy.2004.07.015.
Tullo, A. 2015. "Why Chemical Makers Have Their Eyes on Formic Acid." *C&EN Magazine*, December 7. https://cen.acs.org/articles/93/i48/Chemical-Makers-Eyes-Formic-Acid.html.
Vedros, K.G., R. Christian, and C. Rabiti. 2020. *Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High Temperature Electrolysis Hydrogen Production Plant*. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1691486.
Verfondern K., X. Yan, T. Nishihara, H.-J. Allelein. 2016. "Safety Concept of Nuclear Cogeneration of Hydrogen and Electricity." *International Journal of Hydrogen Energy* 42(11):7551–7559. https://doi.org/10.1016/j.ijhydene.2016.04.239.
Wendt, D., L. Knighton, and R. Boardman. 2022. *High Temperature Steam Electrolysis Process Performance and Cost Estimates*. INL/RPT-22-66117-Rev000. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1867883.
WNA (World Nuclear Association). 2020. "Nuclear Desalination." https://world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-desalination.aspx.
World Nuclear Association. 2021a. "Electric Vehicles." https://world-nuclear.org/information-library/energy-and-the-environment/electric-vehicles.aspx.
World Nuclear Association. 2021b. "Hydrogen Production and Uses." https://world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx.
World Nuclear News. 2020a. "Haiyang Begins Commercial-Scale District Heat Supply." *World Nuclear News*, November 20. https://world-nuclear-news.org/Articles/Haiyang-begins-commercial-scale-district-heat-supp.
World Nuclear News. 2020b. "Finnish Firm Launches SMR District Heating Project." *World Nuclear News*, February 24. https://www.world-nuclear-news.org/Articles/Project-launched-to-develop-Finnish-SMR-for-distri.

Xcel Energy. 2020. "Carbon-Free Hydrogen to Be Produced at Xcel Energy Nuclear Plant." October 15.

Yang, H., J.J. Kaczur, S.D. Sajjad, and R.I. Masel. 2017. "Electrochemical Conversion of CO_2 to Formic Acid Using Sustainion™ Membranes." *Journal of CO2 Utilization* 20:208–217. https://doi.org/10.1016/j.jcou.2017.04.011.

Zhang, Y-X, H-P Cheng, X-M Liu, and J-M Li. 2017. "Swimming Pool-Type Low-Temperature Heating Reactor: Recent Progress in Research and Application." *Energy Procedia* 127(September):425–431. https://doi.org/10.1016/j.egypro.2017.08.110.

Zhang, Z., Z. Wu, D. Wang, Y. Xu, Y. Sun, F. Li, and Y. Dong. 2009. "Current Status and Technical Description of Chinese 2×250MWth HTR-PM Demonstration Plant." *Nuclear Engineering and Design* 239(7):1212–1219. https://doi.org/10.1016/j.nucengdes.2009.02.023.

6

The Challenge of Project Management and Construction

Nuclear power has already made a significant contribution to low carbon generation over the past 40+ years. However, to make a meaningful contribution toward an even cleaner, more reliable, and economical future energy system, nuclear power plants (NPPs) must be constructed much more effectively and efficiently than has been recently demonstrated in the United States and Europe. Even if advanced reactors can be built in a factory and installed on-site to avoid the pitfalls experienced with current nuclear build projects, they must be cost and risk-competitive with other low-carbon technologies in a changing global energy system. Yet, the expectation that new reactor designs could overcome the delays and cost overruns that have plagued the industry remains to be tested.

As stated in Chapter 4, four of the five elements of a successful nuclear program fall within the scope of project management: (1) completed design prior to construction; (2) a fully detailed development schedule that incorporates adequate quality assurance (QA) oversight; (3) adherence to the detailed build schedule; and (4) sustained learning effects from repetitive builds of the same design. More specifically, the ballooning costs of NPPs are directly related to overruns in the Engineering, Procurement, and Construction (EPC) scope of work, and in particular, the "civil" work (non-nuclear portions of the plant) required to construct the plant and install the reactor on the site (see Table 6-1). NPP EPC project managers have to contend with a variety of risk types, including technological, quality, commercial, construction, supply chain, regulatory, organizational, and process risks. In addition, projects can often exhibit high levels of risk derived from their often-compressed schedules, inadequate or uncertain budgets, designs that are near the feasible limit of achievable performance, and frequently changing requirements.

In contrast to existing light water reactors in the United States and the EPC deployment model that has been used to build them, the smaller-scale and simpler design of many new and advanced reactors presents an opportunity for a highly standardized product-based deployment model whereby many multiple units of the same design are manufactured in a factory. While this product-based approach theoretically addresses all four of the criteria listed above, it relies on the assumption that a large nuclear workforce to operate the plants, and a sufficiently large nuclear-grade manufacturing base will exist, and that there will be sufficient demand for the reactors to justify developing the workforce and manufacturing base. The advantages and drawbacks of this approach are discussed in two sections of this chapter: Understanding the Life Cycle of a Nuclear Project and Product Deployment Models.

This chapter first describes each phase of the life cycle of a nuclear project, beginning with an overview of the human capital challenge, which serves as a primer for the planning phase section. The planning phase section discusses optimism bias, organizational learning and risk management, the potential role of government in a pilot project, design of onsite facilities, design of manufacturing facilities, completeness of engineering design, and supply chain issues. The next section addresses the construction phase, also describing the potential role of digital technologies, and ends by discussing the life cycle phases of a nuclear project including commissioning. The section on the life cycle of a nuclear project is followed by a discussion of the product deployment model. The chapter also identifies the limitations in current practice that could potentially hinder the deployment of new NPPs, and each section indicates where owners must develop a robust risk management plan and active mitigation strategies.

TABLE 6-1 Overnight Capital Cost Components as Shown in the Economics Chapter

Cost Component	Share of Total Overnight Capital Costs
Nuclear Island	10–20%
Turbine Generator	5–10%
EPC Costs	10–20%
Civil Work	40–50%
Owner Cost	10%

NOTES: For contemporary and recent nuclear plant projects, capital cost comprises approximately 80 percent of the life cycle cost. The above breakdown of costs will differ for various advanced reactor configurations as presented to the committee. Overnight costs are the costs of a construction project if no interest is incurred during construction, as if the project were completed "overnight." The "nuclear island" consists of the reactor and components inside the reactor containment, but does not include the turbine generator,[1] the condenser, the cooling structures, the generator, or the water intake or outflow structures. The "civil work" includes all the structures, including even the foundation for the nuclear island, that constitute the power plant.
SOURCE: J. Buongiorno, M. Corradini, J. Parsons, et al., 2018, "The Future of Nuclear Energy in a Carbon-Constrained World," Cambridge, MA: Massachusetts Institute of Technology Energy Initiative, https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf.

UNDERSTANDING THE LIFE CYCLE OF A NUCLEAR PROJECT

An intrinsic component of the life cycle of any fixed facility (i.e., installed or constructed on a fixed site) is what is commonly called the *project planning phase*, which includes organizational decisions and all aspects of project definition. Once the engineering design is completed and any necessary licenses obtained, the project can start the *construction phase*. Depending on the licensing scheme used, another license may be needed to progress to the *operations phase* of the project, when the reactor is started up and begins to produce electric power for commissioning, eventually attaining normal operations producing electricity or a combination of energy sources and outputs, depending on the objectives of the owner. Upon completion of its service life, the plant will reach its *decommissioning phase*, discussed in Chapter 7.

Current and past NPP projects in Western Europe and the United States have encountered significant cost and schedule impacts which, in the case of the V.C. Summer plant in South Carolina, resulted in the cancellation of the project after an expenditure of roughly $9 billion (Plumer 2017). Past studies have shown that construction activities that were labor intensive and required more engineering and construction supervision to ensure compliance with standards, including safety standards, are the ones where the most cost growth is seen (Eash-Gates et al. 2020). By developing modular technologies such as those under review in the ongoing DOE programs, some of the labor/supervision–intensive activities can be made more efficient, thereby controlling cost. However, problems with either faulty design or quality of delivered components can cause schedule extensions, leading to daily accrual of home office services,[2] salaried field supervision, and significant costs associated with heavy equipment rentals—for example, cranes (see Figure 6-1).

Ample research on the challenges and failures of megaprojects exists and the lessons should be applied to future nuclear project planning and construction (Eash-Gates et al. 2020; Flyvbjerg et al. 2003; IAEA 2012; Merrow 2021; NRC 1999, 2001, 2003, 2004, 2005; Prieto 2011; Tuohy and Yonemura 2008), although it should be noted that past studies have cited negative learning for nuclear (Grubler 2010; Lester and McCabe 1993).

[1] In some advanced reactor configurations such as non-water-cooled SMRs, the turbine generator is integrated into the SMR module (Prieto 2022).

[2] Home office services include engineering design, purchasing and expediting, cost control, and planning and scheduling (Eash-Gates et al. 2020).

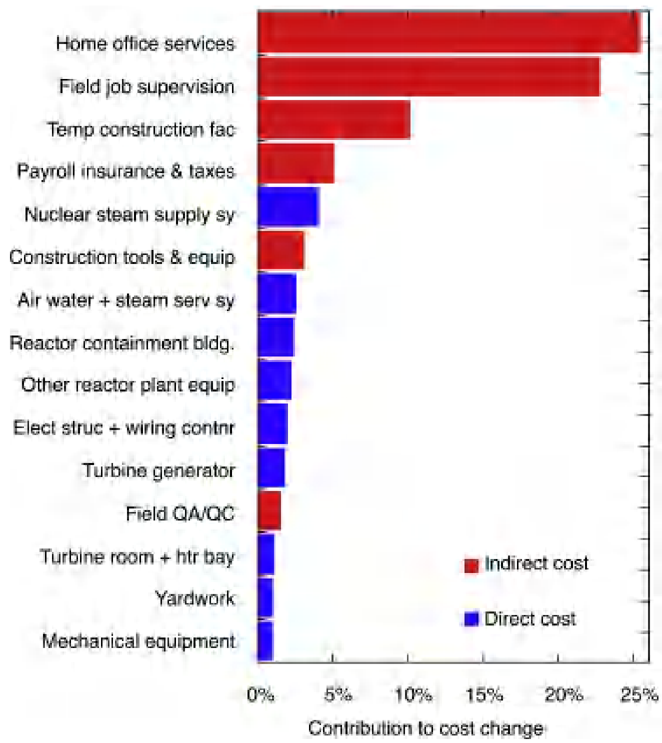

FIGURE 6-1 Sources of nuclear plant cost change from 1976 to 1987.
SOURCE: P. Eash-Gates, M.M. Klemun, G. Kavlak, et al., 2020, "Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design," *Joule* 4(11):2348–2373, https://dspace.mit.edu/handle/1721.1/133049. CC BY 4.0.

The Broader Human Capital Challenge

A critical factor in nuclear project management is availability of the talent necessary to successfully execute any new build. The International Energy Agency lists human capital development as one of the key factors to address if nuclear energy is to play a significant role in energy system decarbonization, stating "[m]aintaining human skills and industrial expertise should be a priority for countries that aim to continue relying on nuclear power" (IEA 2019). Utilities have generally not retained the talent on their staff to execute these large projects given the limited deployment of nuclear technology in the past 30 years in the United States. This shortfall in talent could become equally limiting across the supply chain, operations, and regulatory organizations that must support any large-scale growth in nuclear deployment. It should be noted, however, that the CHIPS and Science Act of 2022 contains provisions[3] that could bolster the nuclear construction workforce.

Nuclear energy technologies require a highly skilled workforce, and the resource development process necessary to support and sustain the technology over an assumed 60+ year service life is complex and expensive. Not only must there be a staff to build the technology, but there must also be a training pipeline to service the plant over many decades; technical experts to develop and manage the fuel cycle; and regulatory, legal and policy experts to develop and manage licensing and oversight.

[3] The CHIPS and Science Act (H.R. 4346), signed by President Biden on August 9, 2022, contains several provisions for training new generations of nuclear engineers and developing the nuclear workforce. The Act establishes a new Advanced Nuclear Research Infrastructure Enhancement Subprogram, which will establish up to four new research reactors. The Act also authorizes additional funding for the University Nuclear Leadership Program (NEUP), increasing its annual funding from $30 million to $45 million from fiscal year 2023 to fiscal year 2025.

The human resource development challenge will certainly manifest itself in the United States if nuclear is chosen as a technology to meet our low-carbon needs. There is already a shortfall in mechanical and electrical engineering talent as well as skilled craftsman in the critical trades (welding, machining, electronics, electrical, etc.) needed to support existing labor force demand (BLS 2022; Wellener et al. 2021). Growth in nuclear development will only exacerbate that shortfall (Emsley 2020). Importantly, the growth in this workforce is also likely to have a diluting effect on supervisory experience at any individual facility. Last, many advanced reactor vendors are moving ahead with technologies that have no experienced operators because they have not been deployed at scale in a commercial setting. All of these factors lead to increased risk, not just in meeting a sustainable growth trajectory that will make a difference for climate but also in terms of safety and operational performance for the overall enterprise. Failure to address the workforce challenge for skilled crafts could impact viability of production for some designs; therefore, it must be addressed comprehensively to ensure workforce shortfalls do not limit deployment capacity.

Finding 6-1: Significant expansion in the deployment of advanced reactor technologies to achieve decarbonization goals will require concomitant growth in the labor force to support not only the construction and operation of these systems, but also to enable the necessary expansion of supporting fuel and supply chains and regulatory and training networks. Development of a wide range of unique technologies may exacerbate this challenge.

Recommendation 6-1: In anticipation of the necessary expansion in workforce to support more widespread deployment of nuclear technologies, the Department of Energy should form a cross-department (whole of government) partnership to address workforce needs (spanning the workforce from technician through PhD) that is comparable to initiatives like the multi-agency National Network for Manufacturing Innovation. The program would include the Departments of Labor, Education, Commerce, and State, and would team with labor organizations, industry, regulatory agencies, and other support organizations to identify gaps in critical skills and then fund training and development solutions that will close these gaps in time to support more rapid deployment. In carrying out these efforts, it will be important to take full advantage of existing efforts at commercial nuclear facilities and national laboratories that already have well-established training and workforce development infrastructure in place.

The Planning Phase

The project planning phase is the key period in the project during which the reactor owner or licensee considers various input parameters, considers alternatives, and risks, and ultimately defines the project scope, method of financing, delivery method, cost, and schedule. To fulfill these functions, the owner must have a strong in-house project team (see Table 6-2; Merrow 2022; National Research Council 2001, 2003, 2004, 2005). The requirement of the owner or licensee's team to plan, develop, and execute the project starts in the planning phase.

Merrow (2011, 2021) recommends that the owner's team (or possibly in certain situations for advanced reactors, the licensee's team) should include substantial technical, engineering, and affiliated personnel (perhaps 150–200 staff for a major project, excluding administrative support), the exact number of which should be scaled to match the size and value of the installation, as well as the delivery method.[4] The team composition and size are not static but will incur adjustments to the skills mix as the project

[4] Delivery method would include such things as contract type, use of factory-manufactured major components or complete reactor, or on-site construction of the plant, as has been the norm to this point in the United States.

progresses (Merrow 2021). In addition, the total team size could be shared by the owner (or licensee) and a dedicated joint venture partner.

Considering that large EPC companies may not have the financial capacity to accept equity risk, such risk is inevitably borne by the owner or licensee (and its financial backers). However, absent a strong internal staff, the owner typically does not have the capacity to manage or even evaluate the risks. This problem is not unique to the nuclear industry: generally, all heavy industry in the United States, Europe, and Australia suffers from three sources of flaws. These include substandard technical expertise, which is outsourced and reduced in capacity; substandard communication among contractors and the owner; and lack of financial accountability (Brewer 2021; Merrow 2021). The trend has been to outsource most aspects of large megaprojects in these countries with the result that there is loss of a capacity to oversee the projects by those bearing the financial risk (Brewer 2021; Merrow 2021). Notably, Asian firms generally did not follow this model (Brewer 2021; Merrow 2021).

TABLE 6-2 Core Owner Team Functions

Business	Project Business Sponsor Lead Project Financial Modeler
Project Management	Project Director Project Managers Interface Management Coordinators
Professional Services	Legal Project-Savvy Human Resources
Engineering	Engineering Managers Discipline Lead Engineers Process Leads Principal Geotechnical engineer (for seismic, ground water, soil conditions) Principal Nuclear Engineer (modified from Merrow's listing of Petrophysicist) R&D Leads (where applicable)
Project Controls	Project Controls Manager Lead Cost Engineer Lead Scheduler/Planner QA/QC Manager
Procurement	Procurement Coordinators Supply Chain Managers Materials Supervisors
Contracts	Contracts Manager
On-site Construction	Construction Managers Labor Relations Specialists
Environment, Health, and Safety	Environmental Lead Permitting Lead Safety Specialist Health Specialist Site Security Advisor
Nuclear Regulatory Team[a]	Regulatory Team Lead Regulatory Legal Regulatory Compliance
Risk Management Team	Risk Analysts Risk Managers (assigned to each identified risk)
Finance	Economics and Investment Representatives Financial Advisors

Local Government and Community Relations	Government Relations Manager Government Liaison Customs Specialist (if needed) Community Relations
Operations and Maintenance	Operations Manager Operations Coordinators (each major area) Maintenance Representative

[a] Additions to Merrow's list from the committee.
SOURCE: Committee generated, modified from E.W. Merrow, 2011, *Industrial Megaprojects: Concepts, Strategies, and Practices for Success*, Hoboken, NJ: John Wiley & Sons.

The committee recognizes that some advanced reactor projects intend to rely on a reactor and associated equipment that could be manufactured entirely in a factory setting. Such reactor installations could eventually include only one reactor on the site or several, depending on demand, economics, and regulatory considerations. Nonetheless, project planning that includes evaluation of risk, economics, alternatives, public engagement, schedule, and quality assurance must still be performed. Supply chains that require materials and parts from external sources will be an important part of the planning. Siting considerations alone include understanding and evaluation of physical considerations (e.g., geologic and soils conditions, elevation of the site above adjacent water bodies, seismic risk, severe weather conditions), as well as community acceptance, workforce availability, and supporting facilities (such as housing and emergency response capability).

In the current environment, utility owners do not have the resources of engineers, planners, and construction professionals to manage large construction projects such as a new nuclear build. The utility owner is more analogous, in organization, to the Department of Veterans Affairs than to the USACE or NAVFAC (see Box 6-1), in that it is unlikely to have an in-house, well-experienced project management team capable of planning and managing a major nuclear project. To circumvent the lack of professional capacity within owner organizations, the committee has considered alternative organizational approaches, and here highlight two such alternative approaches that may merit consideration.

BOX 6-1
Project Management Case Study—Government Owner

The committee has discussed and considered organizations that sponsor, plan, and build megaprojects, albeit not nuclear ones. These organizations include entities such as the U.S. Army Corps of Engineers (USACE), which delivers one-of-a-kind projects such as dams, flood control systems, and disaster recovery facilities and operations, the latter of which is often accomplished under intense public scrutiny and pressure. Likewise, the Naval Facilities Engineering Systems Command (NAVFAC) has delivered megaprojects such as the facilities at the Bethesda, Maryland, Walter Reed Army Medical Center campus, (which became the National Military Medical Center). These two agencies have a common organizational approach in that they constitute a relatively large on-site in-house organization to manage their projects. These organizations typically have in the range of 100 to several hundred technical, engineering, and associated personnel. With organizations of such a size and competency, the USACE and NAVFAC have been relatively successful in on-time, on-schedule delivery.

In contrast, the Department of Veterans Affairs (DVA), while unquestionably competent and qualified to provide the full range of medical care in its hospitals and medical centers, demonstrated it was not able to develop on-site organizations to replicate those of USACE and NAVFAC. Their attempts to plan, design, and construct large hospitals in Denver, Orlando, and Las Vegas garnered national and Congressional attention.

In the instance of the hospital in Denver, Colorado, the costs to taxpayers for the project have already ballooned from an initial $328 million price tag in 2005 to $1.73 billion, with years more construction to go, according to government watchdog groups (Dwyer 2015; Fabris 2016; Wise 2015). House Veterans' Affairs Committee chairman Jeff Miller, R-Fla., has called the agency's entire construction program "a disaster" and the Denver project its "biggest construction failure" (Dwyer 2015; U.S. House Committee on Veterans Affairs 2012). Congress took action in 2016 to assign project and construction management for DVA projects exceeding $100 million to the Army Corps of Engineers (Fabris 2016; Congress.gov 2018).

This discussion about USACE, NAVFAC, and DVA serves to illustrate that while an organization may be fully capable of its core mission (which in the DVA includes medical and hospital care), that same organization may not be capable of performing its own project and construction management. The situation parallels that of utility companies who have as their core business the generation of electrical power yet may not be capable of effectively planning and delivering their own megaprojects, such as NPPs.

To further advance this perspective, a first-hand visit to the project site for the DVA hospital in Orlando in April 2013 revealed that the in-house project team had fewer than 50 technical and engineering personnel on the site. Another visit to the Vogtle project site in August 2014 revealed that the in-house project team there was heavily dependent on augmentation from others. In neither instance did the owner organization comport with the recommended in-house on-site staff size as conveyed by experts' presentations to the committee.[a]

[a] These observations are based on first-hand visits made by committee member James Rispoli.

First, those companies that are interested in pursuing new construction may consider forming a consortium or joint venture to undertake the construction. There are 71 companies that operate NPPs currently in the United States (NEI 2020) and it is not plausible that many of those companies that seek to expand their nuclear involvement could justify the development of a permanent project staff to provide the range of skills that are necessary for project success. By joining forces to create a specialized entity to purse construction, the necessary skilled staff could be assembled to pursue numerous projects and could justify and sustain the wide range of skills that are necessary. The pursuit of multiple projects would allow learning to occur and ideally would enable costs to go down over time. Such an entity could undertake responsibility only for construction but perhaps even could evolve into a vehicle by which multiple companies could engage in ownership of projects, reducing the risk to which each is exposed.

Second, an advanced reactor manufacturer or vendor could consider forming an equity joint venture or consortium with the plant owner and an EPC firm with nuclear build experience to thereby develop the in-house capabilities to plan, manage, and construct the new reactor installations. See Box 6-2 for examples of joint ventures and consortia in the private sector.

BOX 6-2
Examples of Joint Ventures and Consortia in the Private Sector

During the construction of the Advanced Boiling Water Reactors in Japan from the mid-1990s to mid-2000, the vendor, Toshiba, formed an international joint venture with General Electric and Hitachi to manage the EPC activities for several Japanese utilities (e.g., TEPCo). The organization used the appointment of a single primary contract manager with proven expertise in managing multiple independent subcontractors and established a contracting structure in which all contractors (and subcontractors) had a vested interest in the success of the project (Toshiba n.d.). Using modular construction techniques, construction schedules were reduced by nearly 20 percent, and non-civil construction times were reduced by nearly 40 percent relative to the experience with reactor construction before the ABWR buildout (Tuohy and Yonemura 2008).

NuScale Power plans to build its first set of small modular light water reactor power modules for the UAMPS,[a] a consortium of public power utilities in 7 western states, as part of the Carbon-Free Power Project. DOE has provided partial support of the CFPP (DOE 2020). The EPC firm for this project is Fluor Corporation, and Fluor is the majority shareholder for NuScale Power. This is not a typical joint venture, because Fluor was the first major investor in NuScale from its inception. Recently, other energy-related companies have made major investments in NuScale—for example, Doosan Heavy Industries, Samsung C&T, JGC, and IHI.

TerraPower and GE Hitachi launched the Natrium demonstration project in 2020 and announced they are partnering with Bechtel, PacifiCorp, Energy Northwest, and Duke Energy.

The French formed a consortium (Framateg) consisting of Framatome (Westinghouse licensee), EDF (utility owner), Alsthom Atlantique (turbine manufacturer) and Spie Batignolles (construction).

And in the United Kingdom, Rolls-Royce has formed a Small Modular Reactor (SMR) consortium with Assystem, Atkins, BAM Nuttall, Jacobs, Laing O'Rourke, National Nuclear Laboratory, the Nuclear Advanced Manufacturing Research Centre, and TWI (World Nuclear News 2022a).

[a] UAMPS is a subdivision of the State of Utah providing wholesale electric-energy, transmission, and other energy services, on a non-profit basis, to community-owned power systems throughout the Intermountain West. Its 46 members include public power utilities in six states: Utah, California, Idaho, Nevada, New Mexico, and Wyoming.

Finding 6-2: The typical U.S. utility company is not adequately equipped with skilled technical and engineering personnel to plan and manage its own major nuclear construction project. Historical evidence suggests that severe cost and schedule overruns are the result of a lack of these in-house capabilities by the primary owner and operator of challenging projects.

Finding 6-3: Irrespective of deployment model and reactor technology, installation at a specific site will require planning, compliance with environmental regulations and security requirements, consideration of societal concerns, and adaptation to site-specific conditions such as seismic, geologic, groundwater, elevation of the site with respect to adjacent bodies of water, and severe weather considerations.

Recommendation 6-2: Nuclear owner/operators pursuing new nuclear construction should consider the creation of a consortium or joint venture to pursue the construction on behalf of the group, thereby enabling the creation and maintenance of the necessary skilled technical engineering personnel to pursue projects successfully. Alternatively, advanced reactor developers operating within the traditional project delivery model should consider implementing a long-term business relationship, preferably an equity partnership such as a joint venture, or a consortium, with a qualified engineering, procurement, and construction firm experienced in the nuclear industry.

Recommendation 6-3: Department of Energy programs such as the Advanced Reactor Demonstration Program should develop criteria that encourage and incentivize all major government-funded nuclear power projects to include a formal collaborative agreement between the reactor vendor and an experienced development firm to ensure that there is management capacity to complete nuclear construction projects successfully, on budget, and on schedule.

Optimism Bias

One pernicious source of risk in the planning phase of a nuclear project is optimism bias, a cognitive bias that causes a person or group to believe that the chances of experiencing a positive (or planned) outcome are more likely than a negative outcome regardless of the actual probabilities. This can become a particularly nefarious form of risk in the context of project planning when an (invalid) underestimation becomes a benchmark by which a project's success is measured. Moreover, optimism bias can result in inadequate planning for and costing of a nuclear project. The committee is concerned about the presence of optimism bias in the planning for advanced reactors, based on the discussions with vendors and promoters.

Optimism bias does not just afflict the nuclear industry, but other large infrastructure projects as well. Flyvbjerg and others (2003) have identified optimism bias in transportation projects that underestimate costs by 50–100 percent, caused largely by unrealistic initial cost estimation. Some large project promoters may also underestimate costs and schedule through "strategic misrepresentation," a deliberate effort to attract financing from governments or private investors (Flyvbjerg 2006; Flyvbjerg et al. 2003). The resulting cost overruns and schedule impacts may threaten the project's viability (as happened with the Summer nuclear reactor new build) and impact the overall industry.

Simply stated, optimism bias can present a significant threat to the success of a nuclear project. If unrealistic expectations are established related to cost, risk, and schedule, and the expectations are not realized, the reaction of corporate executives, regulators, and the public could exert pressures that are not successfully overcome. Several methods to reduce optimism bias in large projects include forecast accuracy assessments on a combination of forecasts from multiple different sources (Kott and Perconti 2018); the development of standard forecasting language guidelines to reduce interpretive error by evaluators in the assessment of forecast accuracy (Fye et al. 2013); use of functional analysis methodologies in combination with expert panels to cross-check and validate projections (Apreda et al. 2019); and an independent review of the project (Flyvbjerg et al. 2003). In the case of nuclear power, the reviewers must be unaffiliated with vendors and government agencies involved with the projects.

The Department of Energy (DOE), through its Office of Project Management, institutes such independent reviews for its own megaprojects, many of which are projects for nuclear facilities that are unique or first of a kind (FOAK) (DOE 2010). DOE instituted a mandatory requirement for Independent Cost Estimates (ICEs) for its megaprojects. A cost/size threshold is set, above which the project must undergo an ICE that includes technical and programmatic risk. Typically, these ICEs are performed by the U.S. Army Corps of Engineers or another credible organization.

It is during the planning phase that major decisions are made, including decisions on financing, siting, technology, planned construction or installation methodology, and eventually a go/no-go decision. Recent research by Budzier and others (2018) suggests that a process be employed to minimize optimism bias, and thus result in decisions that are more fact and experience based. They suggest comparing with past similar projects, considering the risk involved in those projects, and accordingly adjusting the cost estimate. Such a methodology could be incorporated into an independent peer review, including an independent cost estimate, to assist with the major decisions, as illustrated in Box 6-3. Of course, to incorporate this methodology, there must be a set of FOAK projects upon which to refer, including the factory fabrication portion and the on-site construction elements.

BOX 6-3
Elements to Be Considered in the Planning Phase and Incorporated into an Independent Peer Review

Although cost and schedule overruns manifest in the construction phase, the issues that introduce risk and contribute to cost and schedule overruns often begin in the planning and engineering phases of the project, and include:

1. Lack of design finalization
2. Late-stage design changes owing to errors, regulations, improvements, and so on.
   a. Inadequate design for constructability—it works on paper but cannot be built/assembled easily.
   b. Inadequate safety margin characterization (to allow minor site modifications without reanalysis).
   c. Inadequate environmental health and safety (EHS) engineering and design.
3. Equipment qualification issues (especially system level, as seen with startup and testing phases)
4. Physical fit up issues—sub-modules not fitting as expected.
5. Component integration at the system level—this includes fit-up and performance to setpoints.
6. Inadequate or wrong installation instructions.

7. Inadequate and ineffective rigging/lifting design—it can be physically lifted, but the center of gravity is off.

Finding 6-4: Underestimation of cost, schedules, and risk during the project planning and execution stages can set unrealistic expectations, potentially damaging future prospects for the technology. By ignoring or undervaluing risk, the cost and schedule expectations may not be founded in sound engineering and project delivery expertise.

Recommendation 6-4: The plant owner should mandate an independent peer review involving both a quantitative risk assessment and a qualitative review as part of the plant construction project planning process, especially during a first-of-a-kind new build or first building of an existing design that has had significant changes since it was last built. These could fall under the auspices of the American Society of Mechanical Engineers and the National Reactor Innovation Center, respectively, with assistance from academia and other research organizations (e.g., the Electric Power Research Institute) in the development of the tools and methods. The qualitative independent review should include technical and programmatic risk (to include quality of vendor-fabricated components), the validity of cost estimation elements, schedule realism, and the impact of these on cost; the quantitative risk assessment should include stochastic modeling for schedule and cost estimates. Similar reviews should be conducted when the cost and schedule estimates are more mature, at both 35 percent and 95 percent design completion.

Organizational Learning

To improve cost and schedule performance on nuclear power projects, there is a need to ensure that experience from current and prior projects can be effectively carried forward for future projects. A 2015 study by Talabi and Fischbeck found evidence of learning in NPP operation and maintenance, but not in NPP construction. The study assessed the performance of constructors of U.S. plants, which include General Electric, Babcock and Wilcox, Combustion Engineering, and Westinghouse. To explore the effect of constructor experience, the relationship between experience and both cost and schedule overruns was assessed. Figure 6-2 and Figure 6-3 respectively show the relationship for percentage cost overruns and schedule delays relative to constructor experience. The results show that there is no appreciable relationship, suggesting that level of constructor experience is not an explanatory variable for cost and schedule overruns.

The study showed that after the establishment of the Institute for Nuclear Power Operators (INPO) in December 1979 as a response to the Three-Mile Island accident, there was a marked decrease in the yearly O&M cost trend and improvement in O&M performance citing the NRC's safety improvement observations for nuclear power (Talabi and Fischbeck 2015; USNRC 2009). INPO, a not-for-profit that promotes O&M organizational learning,[5] demonstrated how this type of learning can improve O&M cost and performance for power plants. For nuclear construction cost, there is no dedicated organization or vehicle for sharing the knowledge gained across projects and over construction periods. Thus, a similar program for the planning and construction phase of advanced reactors could add value.

[5] Organizational learning is the process by which an organization improves itself over time through gaining experience and using that experience to create knowledge. The knowledge created is then transferred and preserved within the organization.

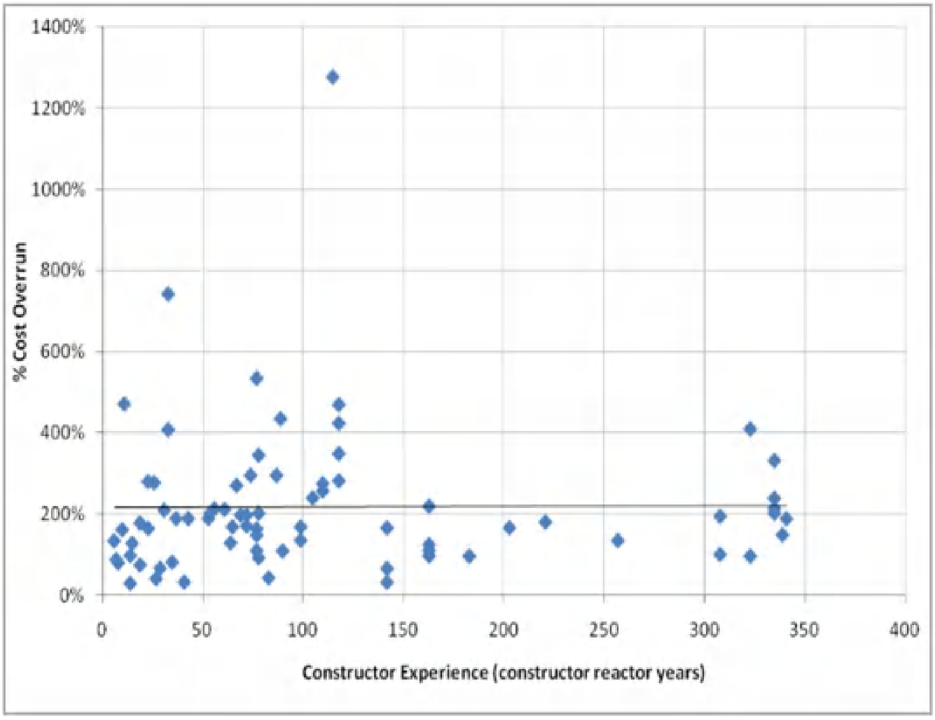

FIGURE 6-2 Nuclear construction cost overruns and constructor experience.
SOURCE: Committee generated using data from U.S. Energy Information Administration, 1986, "Analysis of Nuclear Power Plant Construction Costs," DOE/EIA-0485, Office of Coal, Nuclear, Electric and Alternate Fuels, https://www.osti.gov/biblio/6071600.

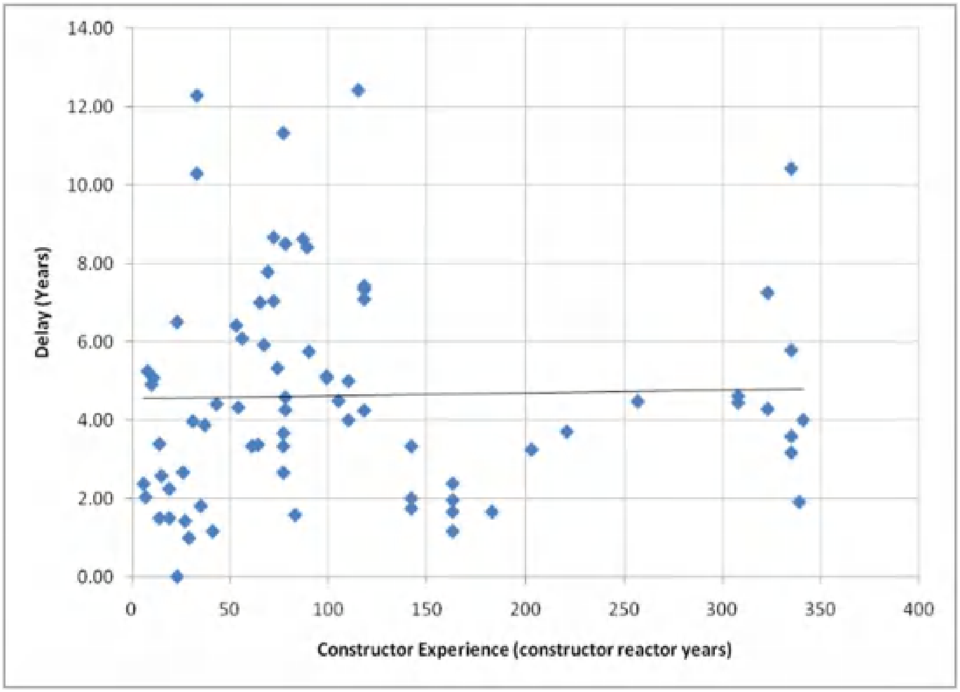

FIGURE 6-3 Nuclear construction schedule delays and constructor experience.
SOURCE: Committee generated using data from U.S. Energy Information Administration, 1986, "Analysis of Nuclear Power Plant Construction Costs," DOE/EIA-0485, Office of Coal, Nuclear, Electric and Alternate Fuels, https://www.osti.gov/biblio/6071600.

Finding 6-5: Although cost and schedule overruns tend to manifest in the construction phase, the causes are often created during the prior planning engineering and procurement phases based on issues such as inadequate design review, component qualification issues, and inadequate installation instructions. This issue is compounded by the fact that there is no readily accessible evidence (e.g., lessons-learned data) that would support and enhance the industry-wide learning that can lead to improved cost and schedule performance over time for nuclear projects in the United States.

Recommendation 6-5: The Department of Energy (DOE) Office of Project Management should partner with an appropriate organization such as the Electric Power Research Institute (EPRI) to build on their lessons-learned repository to provide reactor developers with guidance for risk identification, assessment, and mitigation based on historical occurrences and industry-wide experience. The repository should include a Standard Risk Register for DOE's recent nuclear facilities projects and for nuclear power plant construction (to be developed by the National Reactor Innovation Center), and a standard of practice for nuclear power engineering, procurement, and construction (EPC) projects (perhaps developed by EPRI and the Nuclear Energy Institute). The American Nuclear Society should be encouraged to provide development of a nuclear EPC learning and engagement track.

Design of Onsite Facilities

Advanced reactor developers are planning to use several different configurations for deployment. While it may be possible to factory fabricate some portions of buildings/facilities, all new configurations will still require some level of on-site construction. In one example, the design requires placing nuclear components 90 feet below grade; in others, non-nuclear equipment such as steam turbine generators and ancillary equipment will require site preparation, foundations, and other typical civil, electrical, and mechanical work requiring traditional engineering design for on-site construction.

The challenges with the non-factory fabricated on-site construction are viewed in a similar way as other contemporary large construction projects. The design team must consider a host of environmental and site-specific factors, such as the flood zone, severe weather threats and impacts, seismic zone, groundwater and surface water environmental considerations, how the local construction environment could affect cost and schedule, and similar factors. While the reactor fabricator may specify the parameters for on-site non-nuclear supporting facilities and infrastructure, typically the owner of the site, along with the design team, would be the responsible and accountable entity to provide the engineering design for the overall site.

The committee views the factory fabrication of the nuclear reactor and other nuclear island components as a potentially positive evolution in the nuclear industry. But engineering and construction will still need to consider specific site characteristics and location. In other words, notwithstanding the standardization of the reactor itself and related nuclear components, the remainder of the engineering work could be susceptible to inadequate risk identification and mitigation, challenges posed by individual site conditions, and other requirements that negate the practicality of a standardized design for multiple sites. Given that there are multiple configurations of advanced reactors, and each one may require civil work installations that differ from others, it is recognized that the challenges will vary from reactor design to design.

Design of Manufacturing Facilities

Many of the new reactor designers plan to use a factory-built modular design model for the vast majority of major component construction. Not only will the factory require good engineering design, but owners will also have to ensure that nuclear quality materials and workmanship are available and planned. The experience in the factory construction of modules in the U.S. AP-1000 new build for the Summer and Vogtle plants was fair warning of what can go wrong and result in large cost overruns and schedule impacts. The modular construction for GW-scale reactors provides valuable lessons to be learned that bear on the factory manufacturing approach which is envisioned by SMR developers. In the following subsections, the committee discusses on- and off-site manufacturing challenges and common cause manufacturing issues. The shipyard manufacturing approach, proposed in a 2018 MIT study by Buongiorno et al., is discussed in the next section on Product Deployment Models.

Recent experience with power reactor construction in the United States and Europe offers significant lessons for potential new reactor vendors. Plants under construction in these countries have all suffered from being over time and over budget. Every example outlined below is a near-FOAK plant (near, because similar models of both were constructed and brought online in China). These recent experiences highlight significant quality control challenges that await new and advanced reactor designs—challenges that need to be carefully thought through ahead of time.

On-Site Manufacturing Challenges

Framatome's European Pressurized Water Reactor (EPR), for instance, began construction at the Olkiluoto plant in Finland in 2005. Original plans suggested the plant would be commissioned in 2009. By 2006, problems with the concrete basement, the steel liner, the welding, and the safety culture had all surfaced. By 2015, AREVA, the reactor designer and constructor had technically gone bankrupt. In 2019, a vibration issue emerged, and the startup of the plant was delayed by the regulator. The Olkiluoto plant connected to the Finnish power grid in March 2022 but is not scheduled to start regular electricity production until March 2023 as a result of impeller cracks identified in October 2022 (TVO 2022). The original cost estimate for the plant was €3 billion; now costs are estimated at €11 billion (Schneider and Froggatt 2021).

Off-Site Manufacturing Challenges

Framatome's EPR in France, under construction in Flamanville, began construction in 2007, with a projected end of construction in 2012. By 2015, it was revealed to the regulator that substandard carbon steel had been used in the reactor pressure vessel head, which, finally, was determined to be acceptable after extensive analysis by the regulator. In 2018, 53 welds on safety systems had to be redone. As of the writing of this report, the plant has yet to start up. Cost overruns in Flamanville are worse than for the Finnish plant: originally estimated to cost €3.3 billion, the current cost estimate is €12.7 billion (Mallet 2022).

A similar story exists for the new builds of Westinghouse's AP-1000 design, currently under construction at the Vogtle plant near Augusta, Georgia. Similar to the EPR plants, costs have ballooned from $14 billion for two reactors to over $30 billion (ANS 2022). Two additional AP-1000 reactors were partially constructed at the VC Summer plant in South Carolina before being abandoned in July 2017 by the utility owing to skyrocketing costs and significant delays.

The appeal of the AP-1000 design was its increased passive safety features and modular design elements, which led Westinghouse to believe that factory-produced modules would be more economical than previous construction. Westinghouse claimed, "plant costs and construction schedules benefit directly from the great simplifications provided by the design and [because of] modular construction techniques" (World Nuclear Industry Status Report 2017). The idea was that by having most of the fabrication done in factories, the quality and schedule flexibility associated with reactor construction would be improved, and it would be cheaper to use highly skilled labor in a factory setting instead of in the field, as was done with the previous generation of reactors.

The Shaw Modular Solutions factory in Lake Charles, Louisiana won the contract and skilled labor for the plant was sourced from the nearby offshore oil platforms. Almost immediately, problems appeared when Shaw issued a stop-work order in 2010 after an in-house inspection found inferior welds and welders accepting welds that they had not made. By 2013, ownership of the Lake Charles plant was transferred to Chicago Bridge & Iron, but the problems with the welds persisted. In 2015, Westinghouse acquired the Lake Charles plant, but the welding problems continued and by 2017, Westinghouse itself declared bankruptcy, and VC Summer abandoned its AP-1000 new builds.

The problems at the Lake Charles plant meant that many of the welds done on the modules that were delivered to the Vogtle plant for installation had to be completely redone. Poor welds occurred so frequently that the Vogtle plant set up its own welding building to reweld the factory welds. All of this contributed to cost overruns and time delays. Additionally, the AP-1000's problems were not limited to the United States: the two Chinese plants had problems with their squib valves (pyrotechnically activated valves in a safety system) and reactor coolant pumps, the latter of which had to be rebuilt because the impeller cracked. A contractor, Curtis-Wright, made the pumps, but Westinghouse found itself on the hook to fix the pumps.

The experience of building new reactors in the United States, Europe, and China suggests that it is difficult to ensure that the project goes right, and that nuclear-quality work is done during manufacture and construction. Furthermore, factory-fabricated modularization does not necessarily solve problems—it may in fact introduce generic (and therefore widespread) problems that lead to delays and increased costs. However, these issues can be anticipated, and the risk can be mitigated, as described below.

Common Cause Manufacturing Issues

The production of several reactors or reactor components from the same facility creates a coupling mechanism that allows a root cause deficiency to propagate through multiple products that are produced at the facility. These deficiencies may be owing to intrinsic issues within the facility, or extrinsic issues such as supplier quality deficiencies. Intrinsic deficiencies may be in the form of human factors, processes, or tools. Manufacturing related coupling mechanisms may be observed where a one-to-many relationship exists between software and hardware used in production, as well as errors by manufacturing staff and procedures.

Manufactured nuclear systems may also experience cascading failures, where the issue is not observed at the component level, but rather at the integrated system level. Examples include fit-up issues where individual components may appear to be correctly built, but do not fit together or work properly as a system. Other manifestations of cascading failures include system level performance outside of target values or failed system level qualification, where individual components within the system may perform and be qualified within target values but fail at the system level. Although these failures are seen at the system level, they may be caused by component level manufacturing issues.

A specific example of this issue occurred with the reactor vessel head assemblies of a major reactor vendor, where manufactured components were inspected and qualified prior to shipping, but the components did not fit correctly when integrated at the construction site.[6]

Mitigation of this risk can be especially challenging for first-of-a-kind designs as there is a lack of experience as to where and when these manufacturing risks may be observed. Historically, some common cause failures have not been observed until several years after a fleet of reactors is in operation, as was seen with the light water reactor alloy 600 issues. Hence, there is some uncertainty about the manifestation and consequences of these manufacturing risks, and vendors could consider the following mitigation strategies:

[6] This observation is based on committee member Sola Talabi's first-hand experience as a risk manager at Westinghouse from 2001 to 2014.

- Provision of additional safety and system margin for manufacturing related unknown risks that may affect system level performance and reliability.
- Design for installation flexibility which includes applicable relaxation of tolerances, and maneuverability of components during system level integration. An example of maneuverability is loose flanges between duct sections to allow for site adjustment prior to final tack welding on site.
- Employment of digital technology and use of the digital twin to provide greater assurance at point of manufacture/fabrication so that required design tolerances are complied with (or being met).
- Use of Common Cause Failure (CCF) analysis as a predictive tool rather than just an investigative tool. This is similar to the use of probabilistic risk analysis to identify limiting elements in a system from a safety standpoint. Similarly, the CCF can be used to identify potential manufacturing-based issues that may manifest at a system integration or operational level.

Completeness of Engineering Design

Chapter 4 describes the economic challenge facing advanced reactor developers in making initial entry to energy markets, noting that a significant factor that may limit market entry is the anticipated front-end “sunk cost” for nuclear. Capital costs for nuclear have historically been quite high and schedule duration (and risk of schedule extension) can add significant financing costs to the capital cost bottom line. The necessity for production stoppage to address incomplete design or incorporate late design/performance changes has often contributed to schedule slips. For example, design change had a significant impact on cost growth and schedule slip for the Vogtle AP1000 development (Ingersoll et al. 2020a). Although the initial design had been approved by the NRC after a 4-year review period, construction at Vogtle was delayed by almost a year as Westinghouse incorporated design updates based on experience from AP1000 builds that had begun in China. There was also an externally driven update in 2009 as the NRC changed aircraft protection requirements for new developments, again delaying construction (Ingersoll et al. 2020a).

Completeness of engineering design has been a recurring issue for project cost and schedule execution across multiple industries, from civil construction to shipbuilding to defense weapons systems development (Shamsudeen and Biodun 2016; Blickstein et al. 2011). Often, design completeness rests on a full accounting for the parameters that govern the design or the “basic data.” One analysis of industrial megaprojects found that roughly 90 percent of projects that failed to appropriately scope the basic data and finalize the design at the appropriate stage of the development process suffered from cost growth versus 20 percent of projects with few basic data errors (Merrow 2011). If advanced nuclear developers are to keep capital costs in control, designs must be as complete as possible prior to commencement of construction. A recommended rule of thumb is that engineering detailed design should be 95 percent complete before moving to project execution (Merrow 2011).

AACE International is the generally accepted cost engineering organization, developing and issuing best practices and other materials to assist with development of accurate cost estimates in the construction field. AACE International has issued a series of Recommended Practices (e.g., No. 17R-97 and 18R-97) which include “classes” of cost estimates. A summary table is provided in Table 6-3.

TABLE 6-3 Cost Estimate Classification[a]

	Primary Characteristic	Secondary Characteristic			
Estimate Class	Level of Project Definition Expressed as % of complete definition	End Usage Typical purpose of estimate	Methodology Typical estimating method	Expected Accuracy Range Typical variation in low and high ranges[b]	Preparation Effort Typical degree of effort relative to least cost index of 1[c]
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgement, or Analogy	L: –20% to –50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: –15% to –30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly-Level Line Items	L: –10% to –20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: –5% to –15% H: +10% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: –3% to –10% H: +3% to +15%	5 to 100

[a] Table used with permission of AACE International, 726 East Park Ave., #180, Fairmont, WV 26554. Email: info@aacei.org; Phone 304.296.8444; website: web.aacei.org.
[b] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/– value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50 percent level of confidence) for given scope.
[c] If the range index value of "1" represents 0.005 percent of project costs, then an index value of 100 represents 0.5 percent. Estimate preparation effort is highly dependent on the size of the project and the quality of estimating data and tools.
SOURCE: Association for the Advancement of Cost Engineering International, 2005, "Cost Estimate Classification System—As Applied in Engineering Procurement, and Construction for the Process Industries' TCM Framework: 7.3—Cost Estimating and Budgeting," https://web.aacei.org/docs/default-source/toc/toc_18r-97.pdf?sfvrsn=4. © 2020 by AACE International, All rights reserved.

In comments provided to the committee, former associate administrator for acquisition and Project Management at the National Nuclear Security Administration (NNSA)[7] Robert Raines states that NNSA "does not authorize construction on the nuclear portion of the work until the design is considered

[7] NNSA, the DOE agency responsible for enhancing national security through the military application of nuclear science, likely has the largest ongoing nuclear construction program in the United States.

100 percent[8] complete [by the designer and can then be] turned over to the owner for review."[9] The evaluation is guided by a sweeping set of Final Design Review Requirements.[10] Raines added, "if there are new technologies, [NNSA] also requires a [technology readiness level] (TRL)[11] of 7 [before granting a design credit in order to minimize uncertainty]. For the non-nuclear components associated with the project, [NNSA] allows work to proceed in accordance with best practices."[12] It should be noted that even when designs/drawings are considered complete by the originator and have passed through a final design review, evaluating complexity in manufacture, fabrication, and constructability is often neglected, leading to rework and reevaluation of the design.

Raines's evaluation of NNSA policy reveals that "[NNSA] has completed over $2 billion in work [over] the past 8 years at $200 million under budget. These statistics are much better than any other nuclear work ongoing—that is, Vogtle, Summer [at the time], Olkiluoto, Flamanville. Before DOE implemented these policies … WTP, SWPF, IWTU, MOX[13] were all estimated and authorized for construction at what was considered 'appropriate' design levels." The former qualitative evaluation undertaken by NNSA proved to be problematic because there was no benchmark to guide the evaluation with the result that authorization was often driven by policy or political considerations. As a result, the projects that used the qualitative language are delivering at 2–4 times over original budget. After the policy change to require careful evaluation of the Final Design Requirements (DOE O 413.3B Change 6, 2021), NNSA nuclear and high hazard projects have been delivered on budget.

Finding 6-6: Incomplete design or late design changes can lead to significant schedule and cost growth.

Recommendation 6-6: Advanced nuclear developers should follow a criteria-based approach to ensure that detailed designs are >95 percent complete before transitioning to full project execution. This approach can be made actionable by the owner through insistence on a more comprehensive assessment of design readiness, including manufacturability of components and adequacy of build materials like concrete and rebar.

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[8] 100 percent design requires that all engineering calculations and engineering drawings for the entire installation be complete and ready to issue to the constructor. Because the owner will likely have comments, some modifications may be necessary, with the result that the design is likely to be closer to 90 percent complete.

[9] Information related to NNSA's projects and design review requirements were provided to the committee in an email from Robert Raines, Associate Administrator for Acquisition and Project Management, National Nuclear Security Administration, Department of Energy, on March 31, 2022.

[10] Final design review (FDR) requirements: (1) Verify that the final design satisfies the established requirements and is ready for implementation. (2) Ensure that detailed analyses, calculations, and tests to validate the design are complete and documented. (3) Verify, as appropriate, that the final product can be manufactured, inspected, assembled, stored, delivered, and installed reliably, safely, and cost effectively. (4) Verify that human performance and human factors considerations are appropriately addressed in the design. (5) Verify that procurement issues have been identified and resolved. (6) Verify that appropriate documentation is available for producing the final product (e.g. drawings, installation procedures). (7) Verify that appropriate test plans for the final product have been established. (8) Ensure the appropriate incorporation of recommendations from previous design reviews. (DOE 2010; Princeton Plasma Physics Laboratory n.d.).

[11] TRL is a type of measurement system used to assess the maturity level of a particular technology (NASA 2021).

[12] Construction on site can start with design at 35 to 50 percent maturity for more standard site support buildings such as the non-nuclear office, warehousing, and other general infrastructure (Raines 2022).

[13] Nuclear Waste Treatment Plant (WTP) (at the Hanford site, Washington State), Salt Waste Processing Facility (SWPF) (at Savannah River site, South Carolina), Integrated Waste Treatment Unit (IWTU) (at INL), and Mixed Oxide Fuel Fabrication Facility (MOX) (at Savannah River site, South Carolina).

Supply Chain Issues

A significant part of project planning will include ensuring that supply chains for major reactor components and fuel supply are available at a reasonable cost and appropriate schedule. There are significant challenges in the supply chain, according to the vendors interviewed by the committee (Cirtain et al. 2022).

A recent DOE report titled *Nuclear Energy Supply Chain Deep Dive Assessment* indicates that the enhancement of the nuclear industry supply chain would have significant positive benefit to the cost of electrical energy production:

> The next generation of nuclear reactors will likely include small modular reactors (SMRs) and microreactors. … One of the main reasons for selecting an SMR is to reduce the amount of construction at a reactor site and rely on more factory fabrication. This move to factory fabrication reduces deployment costs by streamlining facility construction. Currently, none of these factory fabrication facilities exist, and they will need to be established to develop the supply chain for advanced reactors. (Finan et al. 2022)

The challenges to development of this supply chain for advanced reactors are multiple. The vendor base for the manufacture of components to a nuclear quality standard is currently sized to produce replacement components for the existing fleet of operational reactor power plants. The manufacturing base for such components will need to expand. Another aspect of the challenges faced is the potential for counterfeit parts, where parts do not meet the certification standards. In one specific instance, it was discovered that prime contractors performing and managing the construction of a multi-billion-dollar nuclear facility were accused of making false claims involving the procurement, fabrication, and installation of vessels and piping to be installed at a nuclear waste processing plant at DOE's Hanford Site (*United States ex rel. Brunson, Busche, and Tamosaitis v. Bechtel National* 2016). In effect, the government contended that subcontractor-supplied components did not meet NQA-1 standards and that false claims were submitted regarding this issue. This issue was resolved by a settlement agreement between the Department of Justice and the prime contractors. There have been other well-publicized examples of similar issues among them a currently released report by the NRC's Inspector General on February 10, 2022 (Feitel 2022; Gardner 2022).

Prior studies on risk management of nuclear EPC projects have indicated inadequate identification of supply chain risks and inaccurate assessment of the identified risks (Talabi and Fischbeck 2015), as indicated in Figures 6-4 and 6-5. The study suggests that supply chain risks were the least identified, but most frequently occurring risks, and also had the highest cost impacts. Part of the reason is apparently that EPC teams tend to over-identify risks associated with the in-house scope of work, but under-identify external risks associated with their external suppliers.

> Finding 6-7: The supply chain supporting the current fleet of operational nuclear power plants in the United States does not currently have the capacity to provide the unique components necessary for different reactor designs while maintaining sufficient quality, considering the number of builds envisioned by reactor developers. The lack of sufficient manufacturing capacity with strict quality assurance programs poses challenges for both product- and project-based deployment models. Expansion of the supply chain would necessitate implementation of Nuclear Quality Assurance (NQA-1) requirements across an enlarged manufacturing base.

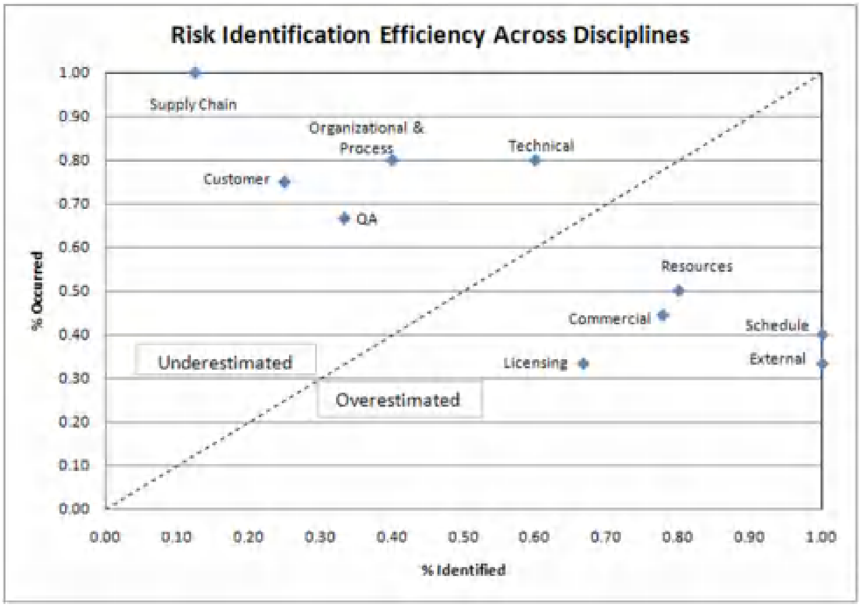

FIGURE 6-4 Risk Identification and Risk Occurrence Relationship across Functional Categories of Risk.
SOURCE: S.M. Talabi and P. Fischbeck, 2015, "Advancing Risk Management in Nuclear Power Plant EPC Projects: An Empirical Evaluation of Risk Management Practices on Steam Generator Replacement Projects," Pp. 545–557 in *Proceedings of the 7th World Congress on Engineering Asset Management (WCEAM 2012)*, W.B. Lee, B. Choi, L. Ma, and J. Mathew, eds., Lecture Notes in Mechanical Engineering, Cham, Switzerland: Springer, https://doi.org/10.1007/978-3-319-06966-1_49. Springer International Publishing, 2015, reproduced with permission from SNCSC.

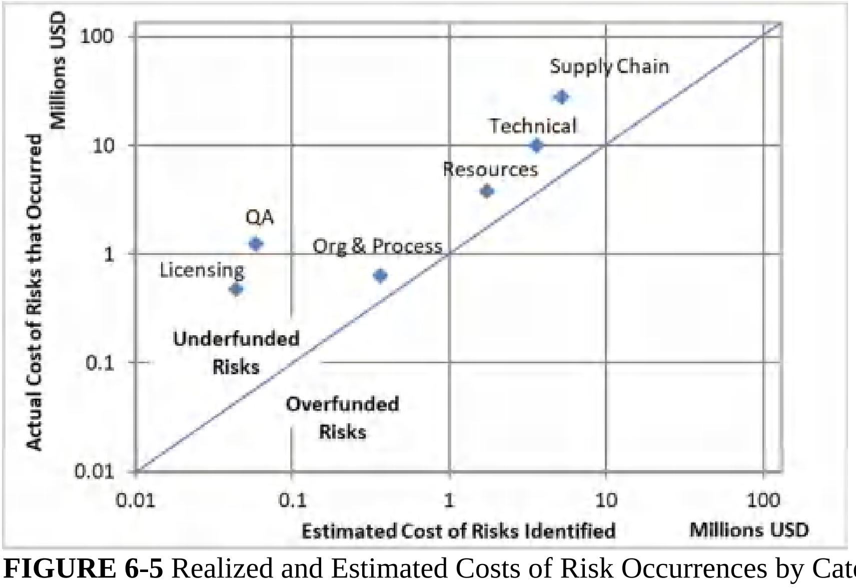

FIGURE 6-5 Realized and Estimated Costs of Risk Occurrences by Category.
SOURCE: S.M. Talabi and P. Fischbeck, 2015, "Advancing Risk Management in Nuclear Power Plant EPC Projects: An Empirical Evaluation of Risk Management Practices on Steam Generator Replacement Projects," Pp. 545–557 in *Proceedings of the 7th World Congress on Engineering Asset Management (WCEAM 2012)*, W.B. Lee, B. Choi, L. Ma, and J. Mathew, eds., Lecture Notes in Mechanical Engineering, Cham, Switzerland: Springer, https://doi.org/10.1007/978-3-319-06966-1_49. Springer International Publishing, 2015, reproduced with permission from SNCSC.

The Construction Phase

Although this chapter focuses on nuclear-specific projects, the recommendations are expected to be robust enough to transcend nuclear power construction and apply to other large energy infrastructure projects. This is justified by the fact that nuclear power ranks in the top 25th percentile of overnight capital cost (Figure 6-6) and represents some of the most significant construction cost and schedule performance challenges.

During the construction phase of a project, the term "Project Controls" is particularly significant. A project controls team effectively receives inputs on progress using a standardized methodology, such as the Earned Value Management System (EVMS) or an alternate system to evaluate trends, identify schedule delays that could impact the critical path and increase costs, and determine appropriate corrective or mitigating measures.

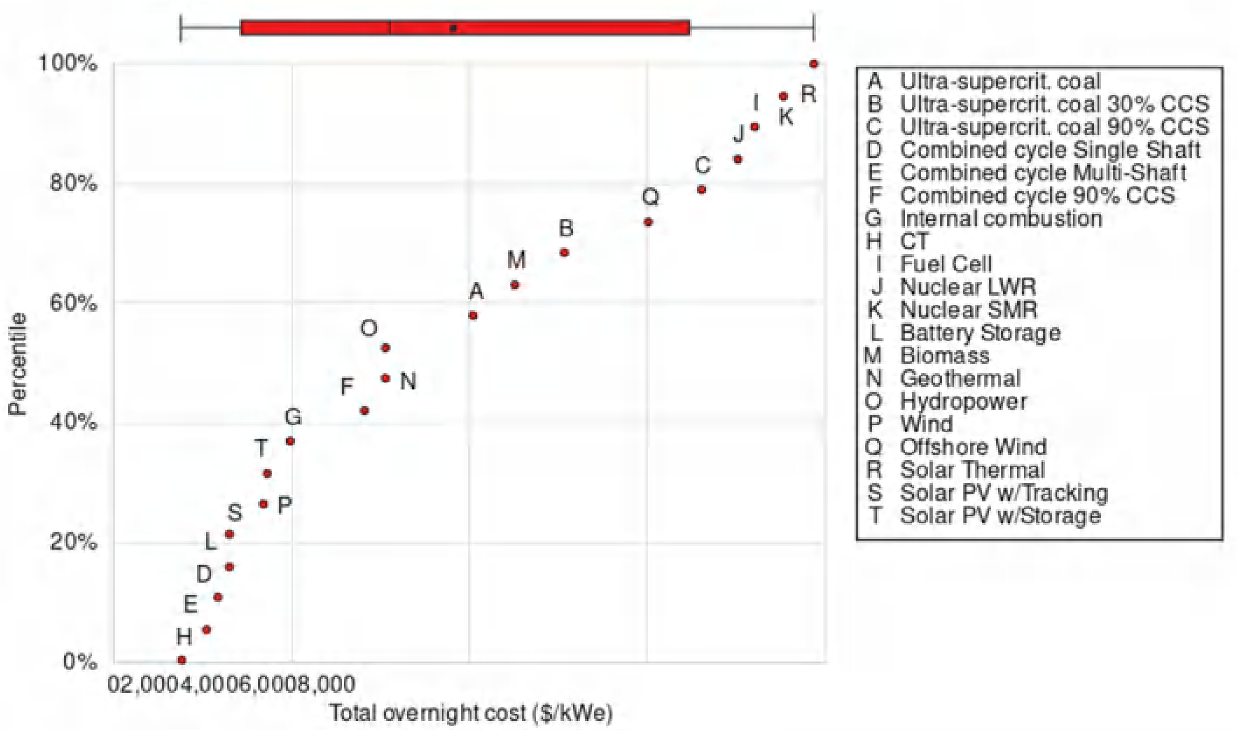

FIGURE 6-6 Overnight Capital Cost Comparison for Generation Options.
SOURCE: Committee generated using data from EIA, 2022, "Monthly Energy Review: Table 7.2a: Electricity Net Generation: Total (All Sectors)," U.S. Energy Information Adminstration.

Potential for Employment of New Technologies

Management of a project life cycle includes a multitude of moving pieces, contractors, and other stakeholders. Poor project management integration, specifically lack of real-time oversight and communication between groups of collaborators, has been cited as one of the main reasons for the failure of the VC Summer NPP (Beck et al. 2016). In an effort to streamline parts of this process and minimize errors imparted by miscommunication, significant federal funds are currently going into various digital engineering (DE) concepts.[14] DE is a systems design approach to use computer technology to integrate the management of a project life cycle. Research at INL has shown that new DE platforms can produce significant impacts in various construction projects, including schedule reductions, productivity increases, and cost avoidance. Benefits of utilizing DE include reduction of data errors that go undetected by the larger system as information flows through the project life cycle, better predictive capabilities, better communication between engineers and on-site personnel, and improvements in future maintenance once a project is complete (Ritter 2021).

Of particular interest in DE research is the idea of a digital twin, whereby on-site construction and installation could be compared to the three-dimensional design by dedicated software (Han and Gupta 2021). In some cases, digital twins are being incorporated into model-based systems engineering (MBSE) approaches to allow an integrated approach to product development that more readily tracks changes across a full product life cycle. Digital twins of Gen III NPPs have been developed in recent years—work by GE has demonstrated up to $1.05 billion in cost avoidance thanks to the predictive capabilities of their digital twin systems (Miller and Ritter 2021). The Versatile Test Reactor planned for INL is being designed to support the progress of multiple new technologies, and digital twinning capabilities are being incorporated to validate advanced modeling tools with real-time operational data.

By such application, design tolerances could be compared to actual dimensions of items while still in the fabrication plant, and the digital twin model can be “moved” virtually to the current as-built condition on-site and “installed” to verify installation dimensional compatibility; thus, more timely decisions could be made concerning the evaluation of any risk owing to non-conformance. Such applications would enable decisions concerning either correction or removal, or possibly acceptance of the feature examined, in near real-time.

Finding 6-8: Digital engineering tools (including but not limited to digital twins) and building information modeling are focused on removing uncertainties that add to cost and schedule during the planning phase by facilitating coordination among all stakeholders and bringing transparency to construction performance. Such innovations could assist with timely identification of quality issues such as tolerances, thus permitting near real-time decisions on acceptance or rejection of the components during installation, which may reduce cost and schedule impacts. Further research on digital engineering tools is needed to determine the value of implementing them in advanced reactor installations.

Recommendation 6-7: The Department of Energy’s Office of Nuclear Energy and Advanced Research Projects Agency–Energy as appropriate should enhance collaboration among entities currently researching and developing digital engineering technologies to support improved vendor fabrication and certification of components. This effort should identify specific capacities that would help nuclear builds in particular.

Given the recurring challenges nuclear developers have faced in controlling cost and schedule during site development, DOE has funded efforts in development of “Advanced Materials and Manufacturing Technologies (AMMT)” as part of the Nuclear Energy Enabling Technologies Program. This effort funds R&D to accelerate technologies that may “reduce the cost and schedule of constructing new nuclear plants, and to make fabrication of NPP components faster, cheaper, and more reliable.” (DOE NE n.d.). Efforts include research into new welding and joining technologies, additive

[14] Entities currently developing these technologies include PowerN, Inc. (ARPA-E spinoff co-founded by Gupta and Han), Reconstruct, OpenSpace, IQSite, Autodesk, Bentley System, and many others working in BIM/reality capture software. There are university researchers who also focus on workflow of how these technologies can be used with different approaches to project delivery (e.g., lean construction and Advanced Work Packaging [AWP]). that are actively studied by institutes like Lean Construction Institute and Construction Industry Institute. This information was provided to the committee in an email from Kevin Han on April 27, 2022.

manufacturing, and modular fabrication. For fiscal year (FY) 2023, DOE requested $7 million in addition to an already insufficient FY 2022 base of ~$25 million for this effort as part of the Cross-Cutting technologies program, reflecting an understanding of the importance of improved construction and deployment technologies.

DOE also recently funded a new initiative called the Advanced Construction Technology (ACT) Initiative funded in FY 2021 for $5.8 million, which aims to

> Facilitate development of advanced nuclear plant construction technologies and approaches through partnerships that could provide game changing benefits to the construction of advanced nuclear power plants. (NRIC n.d.)

The ACT Initiative is structured as a public/private partnership between DOE and GE Hitachi and will be managed by the Nuclear Reactor Innovation Center. The three programs funded by the initiative are

1. Vertical shaft construction, a best practice from the tunneling industry that could reduce construction schedules by more than a year.
2. Steel Bricks™, modular steel-concrete composite structures, much like high-tech LEGO® pieces, which could significantly reduce the labor required on site.
3. Advanced monitoring, coupled with digital twin technology, which can create a digital replica of the NPP structure.

This small-scale research initiative will initially emphasize technology development and will make its findings available to all involved entities.[15] Pending the success of this research and planning, additional funds may be allocated for demonstration efforts. As the effort is structured as a public/private partnership, it may help to jump-start revitalization of private sector competence in this vital aspect of nuclear plant development—efficient site development.

DOE also funds significant research through the Building Technologies Office (BTO) and the Advanced Manufacturing Office (AMO). In FY 2021 alone, BTO funded over $80 million in areas such as development and maintenance of a physics-based whole building modeling engine and large-scale analysis and AMO funded over $70 million in research targeting advanced processes such as additive manufacturing, these offices could be better aligned with DOE-NE efforts to enable greater savings for nuclear construction projects. For example, BTO funding also supports training for existing trades and professionals, and streamlining pathways from education and training to viable careers. DOE NE could also explore cross-department collaborative technology development opportunities (e.g., with the Department of Defense). This could certainly support DOE NE efforts if there were a collaborative emphasis on the most critical skills for new plant construction. While neither BTO nor AMO is aimed at facilitating nuclear construction, DOE NE could coordinate its future research efforts to look for synergies in research thrusts.

DOE is spending billions of dollars for the development of nuclear technologies. Given that the nuclear island constitutes only 20 percent of the cost of a nuclear plant, there should be recognition of the need to ensure adequate funding to reduce overall construction costs. Table 6-1 shows that the civil work typically comprises 40–50 percent of the cost of current generation nuclear plants, and EPC costs typically comprise 10–20 percent of the total cost; moreover, new and advanced nuclear reactors may require more complex civil work, such as excavation (Glaser 2014). These statistics would indicate that by addressing the issues related to the civil work portion of the project, significant risks could be reduced, resulting in improved cost and schedule performance.

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[15] Entities involved in the DOE ACT Initiative include GE Hitachi, Black & Veatch, EPRI, Purdue University, Caunton Engineering, Modular Walling Systems Limited, University of North Carolina at Charlotte, Nuclear Advanced Manufacturing Research Centre, and Tennessee Valley Authority.

Finding 6-9: There are significant research and development efforts under way in advanced manufacturing technology development and advanced processes funded through the Department of Energy (DOE) Building Technologies Office and the Advanced Manufacturing Office. Better alignment of these efforts with DOE's Office of Nuclear Energy's programs may support lower-priced and more streamlined construction of new nuclear sites.

Finding 6-10: Numerous analyses have found that site development challenges have been a primary contributor to cost and schedule overruns for nuclear deployment. Despite this recognition, there is limited research and development activity to develop technologies that can reduce cost and risk in site development that is focused on nuclear plants. For example, $5.8 million was allocated in fiscal year 2022 for the Advanced Construction Technologies Initiative, and some limited funding was provided for materials/manufacturing research (non-specific to site construction) within the Advanced Materials and Manufacturing Technologies Sub-Program portion of the Cross Cutting technologies program. This is dwarfed by the broader non-nuclear-specific programs under way examining advanced production processes and building design processes funded through the Department of Energy Building Technologies Office and the Advanced Manufacturing Office.

Recommendation 6-8: While it is vital to demonstrate that advanced reactors are viable from a technical perspective, it is perhaps even more vital to ensure that the overall plant, including the onsite civil work, can be built within cost and schedule constraints. Because it is likely that costs for onsite development will still be a significant contributor to capital cost, and the ~$35 million in Department of Energy (DOE) funding for advanced construction technologies research and development (R&D) is small in comparison to the hundreds of millions spent on nuclear island technology research, more should be done over an extended period to research technologies that may streamline and reduce costs for this work. DOE should expand its current efforts in R&D for nuclear construction and make these advanced technologies broadly available, including to vendors participating in the Advanced Reactor Demonstration Program Risk Reduction and ARC20 programs.

The Operations Phase

The operations phase requires the early development of a management control system that can cover all facets of testing, data collection, certification, and licensing/transition for operations. The commissioning portion of the operations phase has two significant subphases, non-nuclear testing and nuclear testing.

Non-nuclear testing includes

- Individual preoperational tests of structures, systems, and components.
- Overall preoperational systems tests /cold testing; this cold system testing nominally takes ~8 months for a large scale LWR (Fisher and Moutenot 2020).
- Structural integrity tests, integrated leakage rate tests of the containment and the primary system and secondary system.[16]
- Hot functional testing. Tests at higher temperatures may take as long as 18 months for a large LWR.

[16] Note: these containment checks apply to those technologies that may follow containment designs similar to the existing fleet of light water reactors.

Non-nuclear testing is followed by nuclear testing, which includes

- Initial fuel loading;
- Subcritical tests;
- Initial criticality tests;
- Low power tests; and
- Power ascension tests.

The final milestone for this phase is first grid connection. The timeline from initial fuel loading to first grid connection would nominally be six months for a large LWR.

Following these critical test periods, there is a transition to licensed operations. This typically includes a warranty outage where confirmation of all safety and operational systems is given a final validation. See Box 6-4 for a list of critical issues related to the commissioning process.

While the development schedule for many advanced reactor designs is yet to be determined, the historical schedule and timelines for light water development efforts are instructive and provide a point of departure when considering schedule and potential for contribution of nuclear to decarbonization efforts. A summary schedule, developed by the World Association of Nuclear Operators to aid in readiness for development of new units is shown in Figure 6-7 (Fisher and Moutenot 2020).

BOX 6-4
Critical Issues Related to the Commissioning Process

1. The ability to capture and include lessons learned that may speed commissioning and transition to power operations. In the case of technologies with limited operating experience, consideration may need to be given for a more extended period of operational testing to ensure that design deficiencies are identified before finalizing the design specifications that will be used in Nth of a Kind (NOAK) manufacturing. Evaluation of Structures, Systems and Components (SSC) performance and validation of assumptions made in the Probabilistic Risk Assessment (PRA) for the designs will be critical.
2. Assessment of any containment structures. This step can also drive schedule and validation of acceptability with the regulator, which is key to ensuring the ability to quickly transition to licensed operations.
3. Early assessment/correction of common cause flaws in design and build that may impact follow on unit performance. In this case, the goal is to ensure that any manufacturing process put in place to develop a modular system does not have any faults that may lead to increased risk of a flaw that may impact operations across a fleet of reactors.
4. Enabling staggered approaches for multiple unit manufacture to ensure full utilization of workforce in meeting schedule. To ensure a rapid move from test to operations, manufacturing facilities that may support modular development of SMR systems or development of microreactors must be developed as soon as possible to ensure a product-based approach and avoid a bespoke approach that may not quickly enable learning-curve cost reduction. Of course, before these facilities will be built, it is likely that a sufficient order book will be required that would reduce business risk given the significant capital investment that would be required.
5. For FOAK and the first NOAK units, robust data capture is necessary to ensure any design issues are corrected. This should be incorporated into digital twins and adjustments made as necessary for MBSE models to ensure real-world performance factors are captured to determine potential life cycle maintenance and performance issues.
6. Early interaction with regulator and customer to enable rapid turnaround on test data and grid or power system integration (to include off-grid application considerations).

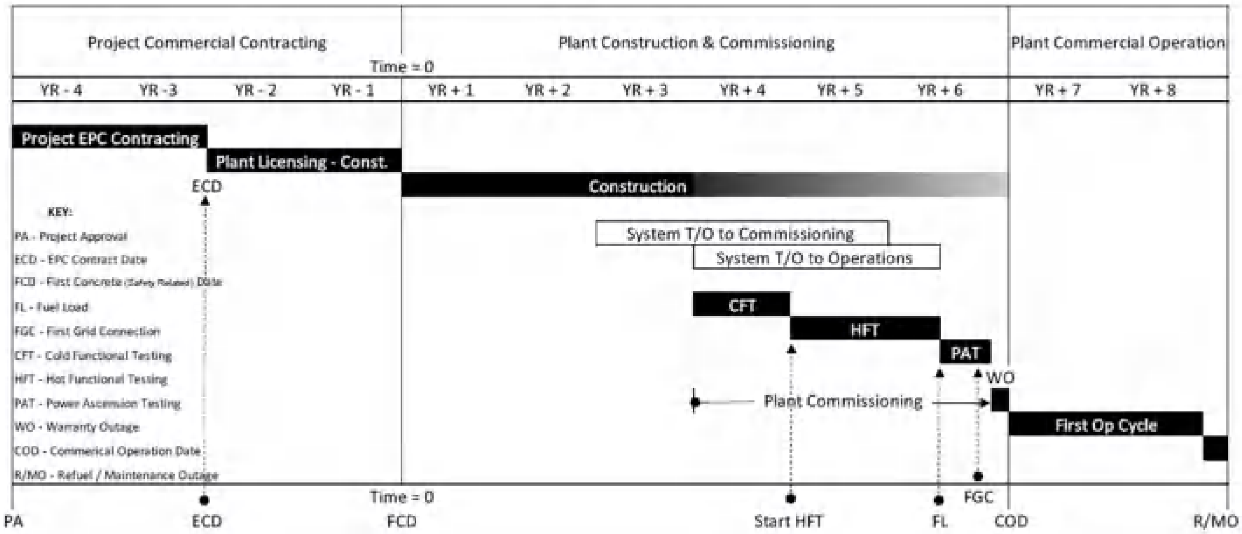

FIGURE 6-7 Standardized sequence of project activities from project EPC contracting to plant operation. SOURCE: R. Fisher and L. Moutenot, 2020, *Roadmap to Operational Readiness: A New Entrant's Guide to Preparing for the Challenge of Safe and Efficient Nuclear Power Plant Operation*, New Unit Assistance Working Group, World Association of Nuclear Operators, September 2020. Copyright © 2020 New Unit Assistance Working Group, R. Fisher, and L. Moutenot.

PRODUCT DEPLOYMENT MODELS

As stated in the introductory section of this chapter, most reactor vendors or developers are planning to employ a product-based approach, that is, the major components, possibly the entire nuclear island, would be fabricated in a factory and delivered to a site, ready to install. The preparatory work on the plant site would be similar to that of any major project, starting with planning, then into engineering design specific to the site, and then construction on site of supporting facilities. Various potential advantages and concerns exist for such an approach:

- **Potential advantages of product-based deployment:**
  - Standardized design for manufacturing can reduce cost and schedule overruns that would otherwise arise from incomplete or late designs
  - Opportunity for improved quality through manufacture in a controlled factory setting.
  - Potential for reduced licensing effort and cost
  - Rapid deployment of many reactors at a time, assuming there is a sufficiently strong order book
  - Scale—benefit of multiples, workforce opportunities
  - Possible reduction in site costs owing to standardized site preparation and seismic isolation
  - Improved workforce optimization and cost assuming there is continuity of operations
- **Concerns with product-based deployment:**[17]
  - Unavailability of parts or components*
  - Lack of sufficient N-Stamp companies, manufacturing capacity*
  - Inadequately sized workforce (size and characteristics)*

[17] Items with an asterisk apply to both product and project deployment models. Because the benefits of a product-based approach are premised on the fabrication of multiple units, the items with an asterisk may present particular challenges.

- Site-specific design and construction considerations such as geotechnical and seismic conditions, ground water, and elevation of the site from bodies of water, despite standardized design for manufacturing will still be required*
- Facility licensing (addressed in Chapter 7) will still be required*
- Infrastructure to transport the reactor to the site will need to be established
- Order book issues
  - Need sufficient orders to justify building a factory and/or modify existing factories up and down the supply chain
  - Backlog of orders is essential for workforce and production line continuity
- Optimism bias (which applies to any major project or product)*
- Common cause failure across entire product output
- New risks that come with scaling up quickly could compromise quality of components

For context in considering these potential benefits and concerns, the committee examines the manufacturing approach to product-based deployment currently under consideration by reactor vendors.

Finding 6-11: A highly standardized product-based approach could improve learning, cost and schedule performance, quality, and speed and scale of reactor deployment. However, the data used to make cost and risk estimates are often based on the assumption that plants are sited at locations with similar characteristics, which will not always be the case.

Finding 6-12: There is currently limited U.S. domestic capability to support a product-based approach to building nuclear reactors outside the naval shipyard environment, although some existing nuclear facilities could be modified to support a manufacturing model and international teaming may be possible.

Recommendation 6-9: The Department of Energy should work with the relevant reactor vendors to develop best practices for the pursuit of a product-based approach to reactor deployment.

The Manufacturing Approach

A primary hypothesis for the vendors of advanced reactors is that they will take advantage of a modular manufacturing approach for development that will help reduce unit cost once market volume supports development at NOAK quantities. This is a reasonable assumption based on historical "product" approaches as seen in the world's shipbuilding, automotive or aircraft industries. The challenge, however, is that this theory has not been tested in the context of complex nuclear energy system development except perhaps in the case of naval nuclear shipbuilding. While the evidence points to success in developing end products for the world's nuclear navies, in many cases there were significant cost and schedule challenges that shipbuilders had to address to better control cost and ensure a consistently high-quality product. Lessons learned from one U.S. Navy program, the Virginia Class Submarine Program, are provided in Box 6-5 (Johnson et al. 2009).

BOX 6-5
Lessons Learned from the Virginia Class Submarine Program

- Need for multi-year procurement "block buy" contracts. This allows development of a stable workforce and bulk purchasing for materials.

- Upgrades to manufacturing facilities to allow multi-unit production. This provides upstream and downstream work to help maximize productivity, especially in the case of process disruptions for one unit.
- Necessity for structured workforce development to build experience. The more experienced the workforce, the greater likelihood of learning and cost savings in multi-unit builds.
- Supply chain focus and support to ensure material readiness.
- Design maturity and standardization. The more stable the design, the greater likelihood that cost and schedule will remain under control.
- Shared development to maintain sufficiently stable workforce in lean years. This is unique to the U.S. Navy submarine program where shipyards shared production responsibility to help maintain shipyard capacity in lean years.

SOURCE: D.C. Johnson, G.M. Drakeley, T.N. Plante, et al., 2009, “Managing Change on Complex Programs: VIRGINIA Class Cost Reduction: Managing Change on Complex Programs,” *Naval Engineers Journal* 121(4):79–94, https://doi.org/10.1111/j.1559-3584.2009.00230.x.

After making adjustments to the program to address many of these issues, the Navy was ultimately able to deliver multiple Virginia Class submarine units with reasonable cost and schedule control. Despite the lessons learned from the Virginia Class program, cost and schedule control for other U.S. Navy nuclear platforms has proven more difficult and many have dramatically exceeded their initial estimated costs. While the Virginia Class program demonstrated that targeted program performance efforts could lead to learning and cost stability, more recent shipbuilding programs such as the Ford Class Nuclear Aircraft Carrier Program have seen ~18 percent rise in procurement costs and a 48 percent increase in acquisition cycle (schedule) (GAO 2020). In the case of this nuclear carrier program, many of the program structures that allowed for cost savings in the case of the Virginia Class were not possible for the Ford Class. The scale and complexity of that platform did not allow multiples to be procured and built simultaneously. Many aspects of the design were of low technical maturity (e.g., a new electromagnetic catapulting system) and in many cases had not even gone through a systems level preliminary design review at contract award. Three obvious takeaways for the advanced reactor community related to these cost and schedule challenges in a “manufacturing approach” are (1) the increased risk of cost/schedule growth tied to project scale and complexity, (2) the risk of incorporating multiple less mature technologies into a single design, and (3) the benefit that comes from the simultaneous build of multiple units.

Beyond naval nuclear development, an analysis of shipyard productivity and costs reflects a significant difference in cost tied to platform complexity that should be considered in development of “manufacturing” business models for advanced reactor development. The OECD does comparative benchmarking analysis of shipbuilding costs that uses a “compensated gross tonnage” (CGT) factor to examine cost versus complexity in shipyard production cycles. As discussed in Ford et al. (2017), a very simple commercial hull form has a CGT factor as low as 0.3, while the most complex naval platform, a nuclear submarine, can be as high as 80. Understanding how this may influence “shipyard” versus site development cost factors would be critical in deciding to take this manufactured approach. Advanced reactor modules built to nuclear specifications would require far more stringent controls than those found in most commercial shipbuilding so it is unclear whether the savings anticipated by vendors touting this “shipyard” approach would materialize. There is also a significant “locational” difference in productivity and cost control that is driven by workforce considerations and production volume. For example, the highest producing shipyards in the world are in South Korea, China, and Japan while other nations lag significantly in terms of productivity and total gross tonnage. It has taken decades and a consistently strong order book for these yards to develop this superior benchmark of productivity. Thus, for each reactor developer to benefit from a “shipyard” approach to manufacturing, advances in productivity, quality and cost reduction will be dependent on steady production so that the manufacturing line equipment and the workforce are steadily used. So, while use of this type of production approach for nuclear reactors may lead to better cost control and savings in some locations and for some vendors, this may not be universally true and the timeline to achieve an order book that would support the type of learning necessary is quite uncertain.

Last, a key assumption by most vendors advocating a manufacturing approach is that by following a centralized "shipyard" approach there will be significant learning and savings. While this may be true, it does not necessarily address what has historically been the largest cost driver for nuclear development—site preparation and civil work. While it may be possible to develop a modular design that can be delivered to the site leading to savings for the components of the nuclear island or balance of plant,[18] this typically accounts for only ~30 percent of the overnight cost for a typical development (Black and Veatch 2012). As addressed in this chapter and Chapter 4, the majority of costs for light water reactor deployment has been from the civil work to include cooling systems, buildings, foundations, seismic isolation, and so on. This work will still be required to some extent, even for factory-produced systems. Until the cost drivers associated with this portion of development are addressed it is unclear how the cost benefit analysis will play out for this revised deployment model. Clearly scale and design of the new systems can help in this regard if the design is standardized and perhaps does not require significant cooling or support facilities development (e.g., facilities to house emergency power, cooling water, etc.).

> Finding 6-13: Advanced reactor developers are considering a manufacturing "shipyard" approach to modular development to better control costs in development. While historical assessments do indicate that a production line approach as seen in shipyard production can lead to cost savings, it is unclear whether this approach will translate to significant cost savings in advanced reactor development because it does not necessarily address site development, which can be a primary cost driver in nuclear deployment.

> **Recommendation 6-10: The Department of Energy should partner with the Department of the Navy and industry to evaluate lessons learned in nuclear shipbuilding to determine the metrics and cost factors that would inform a better understanding of potential cost savings from a manufacturing approach to nuclear new builds. The evaluation would focus specifically on how the engineering facility is set up to enable efficient multiple unit throughput, with considerations to both workforce optimization and setup of internal lines within the facility. Outcomes could include development of standardized tools and analytic methods that would enable better assessment of readiness for commercialization across different nuclear technologies and inform the business cases for development of a nuclear manufacturing facility.**

REFERENCES

AACE International. 2005. "Cost Estimate Classification System—As Applied in Engineering Procurement, and Construction for the Process Industries' TCM Framework: 7.3– Cost Estimating and Budgeting," February. https://assets.sourcemedia.com/8c/d8/6686933e49518782cdc7cc1b577f/bechtel-report-on-v.C.%20Summer%20nuclear%20project%20020516.pdf.

ANS (American Nuclear Society). 2022. "Vogtle Project Update: Cost Likely to Top $30 Billion." Nuclear Newswire. May 9, 2022. https://www.ans.org/news/article-3949/vogtle-project-update-cost-likely-to-top-30-billion.

[18] Balance of plant is a term often used to describe the components of the installations on the site that are not part of the nuclear island and containment structure.

Apreda, R., A. Bonaccorsi, F. dell'Orletta, and G. Fantoni. 2019. "Expert Forecast and Realized Outcomes in Technology Foresight." *Technological Forecasting and Social Change* 141:277–88. https://doi.org/10.1016/j.techfore.2018.12.006.

Beck, R.L., J.D. Burstein, R.A. Exton, J.S. Moore, R.E. Pedigo, J.B. Pettis, et al. 2016. V.C. Summer Nuclear Generating Station Units 2 & 3—Project Assessment Report. Bechtel.

Black and Veatch. 2012. "Cost and Performance Data for Power Generation Technologies." NREL. https://refman.energytransitionmodel.com/publications/1921.

Blickstein, I., J.A. Drezner, M.C. Libicki, B. McInnis, M. McKernan, C. Nemfakos, et al., eds. 2012. *Root Cause Analyses of Nunn-McCurdy Breaches, Volume 2. Rand Corporation Monograph Series*. Santa Monica, CA: RAND Corporation. https://www.rand.org/pubs/monographs/MG1171z2.html.

BLS (U.S. Bureau of Labor Statistics). 2022. "Mechanical Engineers." Occupational Outlook Handbook. September 8, 2022. https://www.bls.gov/ooh/architecture-and-engineering/mechanical-engineers.htm.

Brewer, J.C. 2021. "Pitfalls of Large Complex Projects," presentation to the Committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States Meeting #3, April 5. https://www.nationalacademies.org/event/04-05-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-3.

Budzier, A., B. Flyvbjerg, A. Garavaglia, and A. Leed. 2018. Quantitative Cost and Schedule Risk Analysis of Nuclear Waste Storage. *SSRN Electronic Journal*. https://www.ssrn.com/abstract=3303410.

Buongiorno, J., M. Corradini, J. Parsons, and D. Petti. 2018. The Future of Nuclear Energy in a Carbon-Constrained World. Cambridge, MA: Massachusetts Institute of Technology Energy Initiative. http://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf.

Cirtain, J., D. LeBlanc, E. Blandford, P. Peterson, K. Singh, J. DeWitte, R. O'Sullivan, et al. 2022. "Open Session with Advanced Nuclear Reactor Vendors." Presentation to the Committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States, Meeting 10, February 1–2. https://www.nationalacademies.org/event/02-01-2022/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-10.

Congress.gov. 2018."H. Rept. 115-1036—To Establish a Commission for the Purpose of Making Recommendations Regarding the Modernization or Realignment of Facilities of the Veterans Health Administration, to Improve Construction and Management Leases of the Department of Veterans Affairs, to Amend and Appropriate Funds for the Veterans Choice Program, and for Other Purposes." Accessed May 12, 2022. https://www.congress.gov/congressional-report/115th-congress/house-report/1036.

DOE (Department of Energy). 2010. "Standard Review Plan—Final Design Review Module." https://www.energy.gov/sites/prod/files/Volume1_J_SRP.pdf.

DOE NE (Office of Nuclear Energy). n.d. "NEET Crosscutting Technology Development." Energy.gov, n.d. https://www.energy.gov/ne/neet-crosscutting-technology-development.

DOE O 413.3B Change 6. 2021. *Program and Project Management for the Acquisition of Capital Assets*.

Dwyer, D. 2015. "Veterans Hospital Dubbed 'Biggest Construction Failure' Gets $100 Million Bailout." ABC News. May 23, 2015. https://abcnews.go.com/Politics/veterans-hospital-dubbed-biggest-construction-failure-100-million/story?id=31256468.

Eash-Gates, P., M.M. Klemun, G. Kavlak, J.M. McNerney, J. Buongiorno, and J. Trancik. 2020. "Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design." *Joule* 4(11):2348–73. https://dspace.mit.edu/handle/1721.1/133049.

EIA (Energy Information Administration). 1986. *Analysis of Nuclear Power Plant Construction Costs*. DOE/EIA-0485. Office of Coal, Nuclear, Electric and Alternate Fuels. https://www.osti.gov/biblio/6071600.

EIA. 2022. "Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2022." https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf.

Emsley, I. 2020. "Employment in the Nuclear and Wind Electricity Generating Sectors." 2020/006. World Nuclear Association. https://www.world-nuclear.org/getmedia/690859bf-ebe6-43a2-bedd-57ddf47ee3ac/Employment-in-Nuclear-Report-Final.pdf.aspx.

Fabris, P. 2016. "U.S. House Moves to Give Army Corps of Engineers Management of V.A. Projects." Building Design and Construction Network. February 19, 2016. https://www.bdcnetwork.com/us-house-moves-give-army-corps-engineers-management-va-projects.

Feitel, R.J. 2022. Special Inquiry into Counterfeit, Fraudulent, and Suspect Items in Operating Nuclear Power Plants. OIG CASE No. 20-022. USNRC Office of the Inspector General. https://www.nrc.gov/docs/ML2204/ML22040A111.pdf.

Finan, A., A. Foss, M. Goff, C. King, and C. Lohse. 2022. "Nuclear Energy Supply Chain Deep Dive Assessment: U.S. Department of Energy Response to Executive Order 14017, 'America's Supply Chains.' " Department of Energy. https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain.

Fisher, R. and L. Moutenot. 2020. Roadmap to Operational Readiness. New Unit Assistance Working Group. World Association of Nuclear Operators. September 2020. https://www.wano.info/getmedia/346d2b79-2c11-4b09-962f-840ef279e6d0/R2OR-Revision-0-Final-for-Publication-September-2020.pdf.aspx.

Flyvbjerg, B. 2006. "From Nobel Prize to Project Management: Getting Risks Right." *Project Management Journal* 37(3):5–15. https://doi.org/10.1177/875697280603700302.

Flyvbjerg, B., N. Bruzelius, and W. Rothengatter. 2003. *Megaprojects and Risk: An Anatomy of Ambition*. Cambridge University Press, pp. 11–12. https://doi.org/10.1017/CBO9781107050891.

Ford, M. J., A. Abdulla, and M. G. Morgan. 2017a. "Evaluating the Cost, Safety, and Proliferation Risks of Small Floating Nuclear Reactors." *Risk Analysis* 37(11):2191–2211. https://doi.org/10.1111/risa.12756.

Fye, S.R., S.M. Charbonneau, J.W. Hay, and C.A. Mullins. 2013. "An Examination of Factors Affecting Accuracy in Technology Forecasts." *Technological Forecasting and Social Change* 80(6):1222–1231. https://doi.org/10.1016/j.techfore.2012.10.026.

GAO (U.S. Government Accountability Office). 2020. "Defense Acquisitions Annual Assessment: Drive to Deliver Capabilities Faster Increases Importance of Program Knowledge and Consistent Data for Oversight." June 3, 2020. https://www.gao.gov/products/gao-20-439.

GAO. 2022. "Nuclear Energy Projects: DOE Should Institutionalize Oversight Plans for Demonstrations of New Reactor Types." GAO-22-105394. https://www.gao.gov/assets/gao-22-105394.pdf.

Gardner, T. 2022. Counterfeit Parts Found in U.S. Nuclear Plants -Inspector General. Reuters. February 10. https://www.reuters.com/business/energy/counterfeit-parts-present-many-us-nuclear-power-plants-inspector-general-2022-02-10.

Glaser, A. 2014. "Small Modular Reactors: Technology and Deployment Choices." Briefing on Small Modular Reactors to the U.S. Nuclear Regulatory Commission, November 5. https://www.nrc.gov/reading-rm/doc-collections/commission/tr/2014/20141105.pdf.

Grubler, A. 2010. "The Costs of the French Nuclear Scale-up: A Case of Negative Learning by Doing." *Energy Policy* 38(9):5174–88. https://doi.org/10.1016/j.enpol.2010.05.003.

Han, K., and A. Gupta. 2021. "AI/ML Driven Innovation for High Precision Construction, Inspections, and Management." Presented to the Committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States, April 6. https://www.nationalacademies.org/event/04-05-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-3.

IAEA (International Atomic Energy Agency). 2012. *Project Management in Nuclear Power Plant Construction: Guidelines and Experience*. Nuclear Energy Series, NP-T-2.7. Vienna: International Atomic Energy Agency. https://www.iaea.org/publications/8759/project-management-in-nuclear-power-plant-construction-guidelines-and-experience.

IEA (International Energy Agency). 2019. *Nuclear Power in a Clean Energy System*. Paris: International Energy Agency. https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system.

Ingersoll, E., K. Gogan, J. Herter, and A. Foss. 2020. *The ETI Nuclear Cost Drivers Project: Full Technical Report*. Lucid Catalyst. https://www.lucidcatalyst.com/_files/ugd/2fed7a_0bf1b6be925b4f729ffcd13a8410d6bc.pdf.

Johnson, D.C., G.M. Drakeley, T.N. Plante, W.J. Dalton, and C.S. Trost. 2009. "Managing Change on Complex Programs: VIRGINIA Class Cost Reduction: Managing Change on Complex Programs." *Naval Engineers Journal* 121 (4): 79–94. https://doi.org/10.1111/j.1559-3584.2009.00230.x.

Kott, A., and P. Perconti. 2018. "Long-Term Forecasts of Military Technologies for a 20–30 Year Horizon: An Empirical Assessment of Accuracy." *Technological Forecasting and Social Change* 137 (December):272–79. https://doi.org/10.1016/j.techfore.2018.08.001.

Lester, R.K., and M.J. McCabe. 1993. "The Effect of Industrial Structure on Learning by Doing in Nuclear Power Plant Operation." *The RAND Journal of Economics* 24(3):418–438. https://doi.org/10.2307/2555966.

Mallet, B. 2022. "EDF Hopeful End in Sight for Long-Delayed, Budget-Busting Nuclear Plant." *Reuters*, June 16, 2022, sec. Energy. https://www.reuters.com/business/energy/edf-hopeful-end-sight-long-delayed-budget-busting-nuclear-plant-2022-06-16.

Merrow, E.W. 2011. *Industrial Megaprojects: Concepts, Strategies, and Practices for Success*. Hoboken, NJ: John Wiley & Sons, Inc.

Merrow, E.W. 2021. "Megaprojects Don't Have to Fail." Presentation to the Committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States, April 6. https://www.nationalacademies.org/event/04-05-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-3.

Miller, M., and C. Ritter. 2021. "Digital Twins in the Nuclear Fuel Cycle." Presentation at the July CURIE Workshop, July 26. https://arpa-e.energy.gov/sites/default/files/ARPA-E%20UNF%20Recycling%20Workshop%20Presentation-Ritter%20and%20Reyes.pdf.

NASA (National Aeronautics and Space Administration). 2021. "Technology Readiness Level." https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level.

National Research Council. 1999. *Improving Project Management in the Department of Energy*. Washington, DC: National Academy Press. https://doi.org/10.17226/9627.

National Research Council. 2001. *Progress in Improving Project Management at the Department of Energy 2001 Assessment*. Washington, DC: National Academy Press. https://doi.org/10.17226/10266.

National Research Council. 2003. *Progress in Improving Project Management at the Department of Energy 2002 Assessment*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10679.

National Research Council. 2004. *Progress in Improving Project Management at the Department of Energy 2003 Assessment*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10931.

National Research Council. 2005. *The Owner's Role in Project Risk Management*. Washington, DC: The National Academies Press. https://doi.org/10.17226/11183.

NEI (Nuclear Energy Institute). 2020. "U.S. Nuclear Plant Owners and Operators." https://www.nei.org/resources/statistics/us-nuclear-plant-owners-and-operators.

NRC (U.S. Nuclear Regulatory Commission). 2009. *Plant Safety Performance After TMI-2 Accident.* https://www.nrc.gov/docs/ML0907/ML090710963.pdf.

NRIC (National Reactor Innovation Center). n.d. "Advanced Construction Technology Initiative." Accessed on February 13, 2022. https://nric.inl.gov/advanced-construction-technologies-initiative.

Plumer, B. 2017. "U.S. Nuclear Comeback Stalls as Two Reactors Are Abandoned." *The New York Times*, August 1, 2017, sec. Climate. https://www.nytimes.com/2017/07/31/climate/nuclear-power-project-canceled-in-south-carolina.html.

Prieto, R. 2011. *The GIGA Factor: Program Management in the Engineering and Construction Industry*. Construction Management Association of America (CMAA), pp. 9–16.

Prieto, R. 2022. "Delivering Next Generation Nuclear Power: The Project Management Challenge Remains." *PM World Journal* XI(VII):July. https://pmworldlibrary.net/wp-content/uploads/2022/07/pmwj119-Jul2022-Prieto-Delivering-Next-Generation-Nuclear-Power.pdf

Princeton Plasma Physics Laboratory. n.d. "Design Review Objectives and Input Documentation." https://evms.pppl.gov/NSTXU_FDR/eng033.pdf.

Reed, S. 2019. "Hitachi to Cease Work on Nuclear Power Plant in North Wales." *The New York Times*, January 17, 2019, sec. Business. https://www.nytimes.com/2019/01/17/business/energy-environment/hitachi-horizon-wales-nuclear-plant.html.

Reuters. 2021. "UPDATE 1-Wales Bids for Hitachi Nuclear Site-Sunday Times." *Reuters*, February 7, 2021, sec. Oil report. https://www.reuters.com/article/wales-nuclear-hitachi-idINL1N2KD02W.

Ritter, C. 2021. "Digital Engineering to Accelerate Advanced Reactor Development." Presentation to the Committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States, April 6. https://www.nationalacademies.org/event/04-05-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-3.

Schneider, M., and A. Froggatt. 2021. "The World Nuclear Industry Status Report 2019." In *World Scientific Encyclopedia of Climate Change*, pp. 203–209. World Scientific. https://doi.org/10.1142/9789811213953_0021.

Shamsudeen, M. and O.N. Biodun. 2016. "Effects of Design Errors on Construction Projects." *International Journal of Scientific and Engineering Research* 7(2):16. https://www.ijser.org/researchpaper/EFFECTS-OF-DESIGN-ERRORS-ON-CONSTRUCTION-PROJECTS.pdf.

Talabi, S.M., and P. Fischbeck. 2013. "Exploring Expert Confidence in Cost Estimates for Nuclear Power Engineering, Procurement and Construction Projects—a Survey of Nuclear Industry Experts." *International Journal of Strategic Engineering Asset Management* 1(4):374–389. https://doi.org/10.1504/IJSEAM.2013.060473.

Talabi, S.M., and P. Fishchbeck. 2015. "Advancing Risk Management in Nuclear Power Plant EPC Projects: An Empirical Evaluation of Risk Management Practices on Steam Generator Replacement Projects." Pp. 545–557 in *Proceedings of the 7th World Congress on Engineering Asset Management*, edited by W.B. Lee, B.Choi, L. Ma, and J. Mathew. Lecture Notes in Mechanical Engineering. Cham, Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-319-06966-1_49.

Toshiba. n.d. Completion of the First Advanced Boiling Water Reactor. Toshiba Science Museum. Accessed February 11, 2022. https://toshiba-mirai-kagakukan.jp/en/learn/history/ichigoki/1996advanced_bwr/index.htm.

Tuohy, J., and H. Yonemura. 2008. "Challenges of Engineering and Constructing the Next Generation of Nuclear Plants," Presented at MIT, Cambridge, Massachusetts, February 2008. https://genderi.org/challenges-of-engineering-and-constructing-the-next-generation.html.

TVO. 2022. "Olkiluoto 3 EPR's Test Production to Continue." *TVO News*, December 21. https://www.tvo.fi/en/index/news/pressreleasesstockexchangereleases/2022/olkiluoto3epr8217stestproductiontocontinue.html.

United States ex rel. Brunson, Busche, and Tamosaitis v. Bechtel National In., Bechtel Corp., URS Corp., and URS Energy & Construction, Inc., Case No. 2:13-CV-05013-EFS (E.D. Wash, 2016). https://www.justice.gov/usao-edwa/press-release/file/913411/download.

U.S. House Committee on Veterans Affairs. 2016. "Chairman Miller Statement on Biggest Construction Failure in VA History." Press Release. September 21, 2016. https://archives-veterans.house.gov/news/press-releases/chairman-miller-statement-biggest-construction-failure-va-history.

Wellener, P., V.Reyes, H. Ashton, and C. Moutray. 2021. "Creating Pathways for Tomorrow's Workforce Today: Beyond Reskilling in Manufacturing." *Deloitte Insights*, May 4. https://www2.deloitte.com/us/en/insights/industry/manufacturing/manufacturing-industry-diversity.html.

Wise, D. 2015. "VA Construction: VA's Actions to Address Cost Increases and Schedule Delays at Major Medical-Facility Projects." Testimony Before the Committee on Veterans' Affairs, House of Representatives GAO-15 332T. U.S. Government Accountability Office (GAO). https://www.gao.gov/assets/gao-15-332t.pdf.

World Nuclear Industry Status Report. 2017. "Westinghouse: Origins and Effects of the Downfall of a Nuclear Giant." *World Nuclear Industry Status Report Essential News*, April 2, 2017. https://www.worldnuclearreport.org/Westinghouse-Origins-and-Effects-of-the-Downfall-of-a-Nuclear-Giant.html.

World Nuclear News. 2022. "Collaboration for Rolls-Royce SMR Deployment in the Netherlands." *World Nuclear News*, August 25. https://www.world-nuclear-news.org/Articles/Collaboration-for-Rolls-Royce-SMR-deployment-in-th?feed=feed.

7

Nuclear Regulation in the United States

Domestic power reactors are tightly regulated by the U.S. Nuclear Regulatory Commission (NRC) in all phases of their life cycle—design, construction, operations, and decommissioning. The NRC is charged with licensing and regulation of plants to provide reasonable assurance of adequate protection of public health and safety, to promote common defense and security, and to protect the environment.[1]

The fundamental design of light water reactors dates from the early days of reactor operation, although there have been significant enhancements to improve operations and safety over the years. The NRC requires compliance with detailed regulations that are tailored to light water reactors (LWRs). The existing regulatory requirements may be inappropriate or inapplicable to non-LWR designs and some of the advanced designs present new regulatory issues. As a result, significant modification or adjustment of regulatory requirements is required to accommodate some of the advanced reactors.

THE REGULATORY PROCESS

All but the two plants now under construction in the United States (Vogtle 3 and 4) were licensed pursuant to Part 50 of the NRC's regulations. Under this licensing process, an applicant first obtains a construction permit (CP). The issuance of this permit involves a careful examination of siting-related issues but requires only a general description of the specific reactor design. While the reactor is under construction, the applicant typically pursues an operating license (OL), which is required prior to the loading of fuel and the commencement of reactor operations. An applicant or an interested stakeholder can challenge the NRC staff's proposed decisions before the Atomic Safety and Licensing Board (a panel of administrative judges employed by the NRC), followed by review by the Commission, and potentially by a U.S. Court of Appeals. The Part 50 process allows an applicant to proceed with construction before assembling all the necessary technical material that is required for an OL, but that presents the risk that the decisions at the OL stage might require extensive retrofits of a substantially completed reactor.

The NRC established a second licensing pathway in the late 1980s (NRC 2018a). Part 52 allows an applicant to apply for a combined license (COL) that authorizes both construction and operations (NRC 2018a). A COL defines the terms that must be satisfied to allow operation, thereby reducing the risk that new requirements might be imposed after completion of construction: Before fuel can be loaded and operations can commence, the NRC ensures that certain inspections, tests, analyses, and acceptance criteria (ITAAC) set out in the license are satisfied. This verifies that the reactor authorized by the COL has been built and that any open issues have been resolved. See Figure 7-1.

Part 52 also allows, but does not require, certain ancillary regulatory actions that serve to provide early resolution of regulatory issues. For example, Early Site Permits (ESPs) allow the approval of a site for a reactor that meets requirements relating to environmental impacts, including evaluation of alternative sites, and site-suitability issues, such as emergency preparedness and security matters. An ESP can be sought before a decision is made to use the site or a specific reactor design is selected.

[1] The National Environmental Policy Act (NEPA) requires federal agencies to evaluate the impacts of proposed actions on the human environment. The NRC complies with NEPA through its regulations in 10 CFR Part 51.

Another important innovation is the opportunity for a vendor to obtain a design certification (DC) for the full design of a reactor's nuclear island, resulting in a rule that can be cited by an applicant for a COL to show satisfaction of all the licensing requirements resolved in the promulgation of the rule. Part 52 also authorizes a standard design approval (SDA), which does not have the full binding effect of a DC.[2] A DC and SDA can be obtained before there is a decision to proceed with construction of the plant. A DC or SDA can be particularly attractive to a vendor because it covers all applications of the design. So, if a given design is constructed at many sites, there is only one regulatory review of the design.

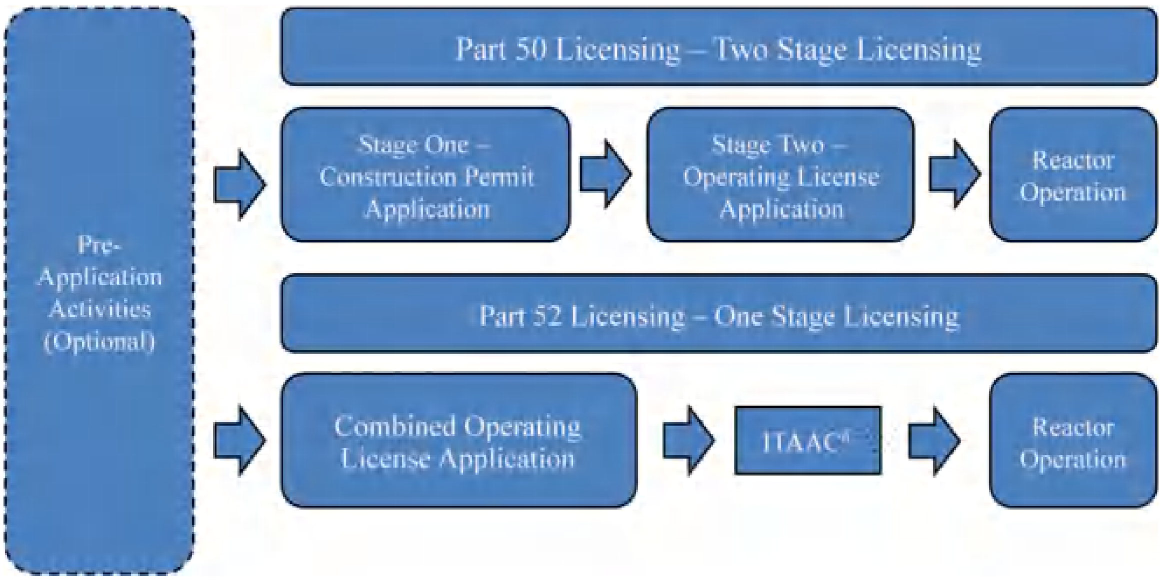

FIGURE 7-1 Two licensing processes for new commercial nuclear power plants in the United States. ITAAC is inspections, tests, analyses, and acceptance criteria.
SOURCE: J. Buongiorno, M. Corradini, J. Parsons, et al., 2018, "The Future of Nuclear Energy in a Carbon-Constrained World," Cambridge, MA: Massachusetts Institute of Technology Energy Initiative.

Of particular interest to the vendors of some advanced reactors is the opportunity to obtain a manufacturing license that allows the fabrication of a nuclear power plant at a location other than the one where it is to be installed and operated. This license may be attractive to vendors that intend to establish a factory to build a reactor to be deployed at many sites.[3]

These various elements of Part 52 reduce regulatory risk because the matters resolved during the approval of the COL, ESP, DC, SDA or manufacturing license cannot be reexamined absent significant and new information that calls into question the previous resolution of an issue.[4] But two problems remain. First, a drawback of a DC, an SDA, or a COL is that each tends to freeze the design at an early

[2] Although the staff is bound by a SDA, it does not affect the authority of the Commission or the Atomic Safety and Licensing Board Panel in reviewing a license application. 10 CFR 52.145.

[3] A reactor manufactured under a manufacturing license may only be transported to and installed at a site for which either a construction permit or a COL has been issued. A manufacturing license applicant may reference a standard design certification or a standard design approval in its application. 10 CFR 52.153.

[4] The risk is not eliminated because of the need to satisfy the ITAAC. Moreover, the NRC has the authority to order modifications of any reactor, so-call "backfits," if the change is necessary to provide adequate protection of public health and safety or if the change is justified by comparison of the costs and benefits of a change. 10 CFR 50.109.

stage. There are issues that can arise as a design is finalized or that are found during construction, which may necessitate regulatory approvals of changes, resulting in delay and expense.[5]

This obstacle can be overcome at least in part if a vendor uses both of the existing regulatory processes. An applicant can pursue a license under Part 50 for the demonstration of the design, thereby allowing the opportunity for problems that arise during construction to be corrected before the final design is submitted for approval of an OL. Based on the experience with the demonstration, the vendor could then adjust its design, if necessary, and seek a DC under Part 52, enabling the vendor to avoid repetitive review of the design in subsequent construction projects.

The second challenge is not so easily overcome. Under either Part 50 or Part 52, the vendor will incur substantial front-end expenses to assemble all the detail that is required to complete the relevant licensing process. (SEAB 2016). These expenses can be very substantial in the case of an OL or a COL in part because of NRC fees (many tens of millions of dollars) (NRC 2020a),[6] but largely because of all the work that is required by the applicant to assemble the necessary tests, analyses, and documentation to support a license application (many hundreds of millions of dollars). This is an issue for any of the advanced reactors because there is a risk that after large expenditures, the NRC might find some features unacceptable or might impose unanticipated and costly additional requirements.

Over the years, the regulatory philosophy of the NRC has also changed. In the early years of nuclear power, the safety requirements were guided by deterministic analyses and engineering judgment, resulting in prescriptive requirements that form the foundation of the NRC's rules. The capacity to undertake sophisticated probabilistic analyses of accident sequences was subsequently developed (NRC 1986). The probabilistic analyses support an approach to regulation in which a high-risk event must be prevented or mitigated to a greater extent than a low-risk event.[7] Such probabilistic risk analyses (PRAs) provide a means to assess whether the existing prescriptive requirements should be relaxed or enhanced. This has resulted in a regulatory system in which risk-informed adjustments constitute an overlay on former regulatory requirements based on deterministic analyses (Kadambi et al. 2020).[8] While the operators of the existing nuclear fleet are supportive of risk-informed initiatives, they generally endorse their usage only for adjustment or, as necessary, for supplementation of the existing prescriptive requirements; the operators value stability in regulatory requirements and are wary of sweeping modifications. As discussed later in this chapter, the vendors of some advanced reactors, on the other hand, seek significant departures from the existing requirements.

Concurrent with the development of probabilistic capabilities, the regulatory philosophy of the NRC, as with other regulators, has evolved to emphasize outcomes rather than prescriptive requirements (Walker and Wellock 2010). That is, the aim of regulation is to specify the safety objective to be achieved rather than a set of detailed engineering-level requirements to meet the safety objective.[9] The licensee is then allowed to determine the optimal way to satisfy the performance objective.

An additional complication in the rigid application of Part 50 and Part 52 to advanced reactors is that many of the advanced reactors present safety- and security-related issues that differ from those of LWRs. If Parts 50 and 52 were taken as the model and the existing requirements for LWRs were adapted to accommodate other technologies, a tailored set of specific regulatory requirements for each different technology would need to be developed. Given the diversity of technologies that the advanced reactor

[5] The Vogtle plants that are being built in Georgia have been long delayed and far exceeded their initial budget. Part of the reason arises from the need to introduce significant modifications of the design that became apparent as construction was under way.

[6] More than 90 percent of the NRC's budget is recovered from fees paid by applicants and licensees. There are proposals to eliminate NRC review fees for advanced reactor license applications. H.R. 6154, 117th Congress, 1st Session (2021).

[7] Risk is determined by consideration of both the probability of the occurrence of an event and the severity of the consequences of that event.

[8] See also the NRC's discussion of the history of risk-informed regulatory programs (NRC 2021).

[9] The NRC often provides regulatory guidance documents that describe a way to satisfy performance-based requirements, but a licensee need not follow this guidance and can propose alternatives.

vendors are proposing or could propose in the future, this would be a huge undertaking. To avoid these problems, there is significant interest in developing a technology-inclusive regulatory framework. In fact, in the Nuclear Energy Innovation and Modernization Act (NEIMA),[10] Congress directed the NRC to develop such a regulatory framework for optional use by licensees by the end of 2027. (The existing licensing pathways under Parts 50 and 52 would continue to be available.) The new rule will encompass not only licensing, but also the regulatory requirements for all stages of the nuclear plant's life cycle. The NRC subsequently committed to promulgation of a final rule, to be designated as Part 53, before the statutory deadline.[11] In the meantime, applicants can pursue the licensing of advanced reactors under Part 50 or Part 52 by pursuing exemptions from existing regulatory requirements where necessary.

The Licensing Modernization Project (LMP),[12] which was supported jointly by nuclear industry and DOE, was undertaken to provide a foundation for the licensing of advanced reactors in the interim before Part 53 is available. It uses probabilistic insights for the selection of licensing basis events (considered in the design and licensing of a plant), as well as for classification of structures, systems, and components to ensure that safety-significant components can fulfill their function (so-called "special treatment requirements"), and for the determination of the adequacy of "defense in depth."[13] The aim is to provide a comprehensive technology-inclusive, risk-informed, and performance-based means to guide licensing in a logical, systematic, and reproducible process. The LMP project has been followed by the industry-led Technology Inclusive Content of Application project (TICAP) to provide guidance on the structure and content of parts of the Safety Analysis Report, a critical element of an application to the NRC for the licensing of a design.[14] At the same time, the NRC is developing guidance for other parts of the Safety Analysis Report.[15]

Some vendors have viewed the LMP approach as overly burdensome. They claim that their designs present so little risk that the sophisticated analyses demanded by the LMP are unnecessary. While not opposing the application of the LMP approach by others, they claim that alternative ways of establishing the safety case for an advanced reactor should also be allowed. For example, Oklo concluded that the LMP process was unnecessarily complicated for its microreactor design and submitted a COL application that was based on a deterministic analysis of safety. The NRC indicated that it was prepared to evaluate Oklo's application, but it subsequently terminated its evaluation without prejudice on the basis that Oklo had not responded adequately to requests for information (NRC 2022c). Oklo has indicated that it will update its application and resubmit.

Extensive work by the NRC, the nuclear industry, and public commenters is under way to develop Part 53. The NRC issued a notice seeking comment on certain preliminary language for the

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[10] See Congress.gov, 2019, "Text—S.512—115th Congress (2017–2018): Nuclear Energy Innovation and Modernization Act," https://www.congress.gov/bill/115th-congress/senate-bill/512/text.

[11] The NRC originally set a deadline of October 2024 (NRC 2021a) but has since extended the deadline to July 2025 (NRC 2023).

[12] See Nuclear Energy Institute, 2019, *Risk-Informed Performance-Based Technology-Inclusive Guidance for Non-Light Water Reactors*, NEI 18-04, Rev. 1, Washington, DC: Nuclear Energy Institute. This guidance has been endorsed by the NRC in RG-1.233.

[13] Defense in depth involves the establishment of multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied on. Defense in depth includes the use of redundant and diverse means for meeting key safety functions, access controls, physical barriers, and emergency response measures. The consideration of defense in depth is a fundamental element in the design of NPPs. See generally International Nuclear Safety Advisory Group, 1996, *Defence in Depth in Nuclear Safety,* INSAG-10, Vienna: International Atomic Energy Agency.

[14] See Nuclear Energy Institute, 2022, *Technology Inclusive Guidance for Non-Light Water Reactors: Safety Analysis Report Content for Applicants Using the NEI 18-04 Methodology*, NEI 21-07, Rev 1, Washington, DC: Nuclear Energy Institute, https://www.nrc.gov/docs/ML2206/ML22060A190.pdf. This guidance is currently undergoing NRC review.

[15] The NRC work is proceeding under the Advanced Reactor Content of Application Project (ARCAP).

contemplated rule.[16] The NRC staff has indicated that the proposed rule will contain two alternative regulatory pathways—a "Framework A" that will be based on the PRA approach developed by the LMP, and a "Framework B" that would not require a PRA, but would use risk insights in a confirmatory role to a largely deterministic analysis.[17] Framework B is based on the approach in the existing Part 50 and 52 while modifying it to be technology neutral. It provides a simplified approach that some vendors argue is appropriate for their designs.

> Finding 7-1: In recognition that advanced reactors present different regulatory issues from light water reactors, the U.S. Nuclear Regulatory Commission (NRC) is allowing a degree of regulatory flexibility under the existing regulatory system (NRC Part 50 and Part 52). It is also pursuing a technology-independent, performance-based, and risk-informed regulatory process for advanced reactors to be promulgated as Part 53. These actions reflect reasonable flexibility by the NRC to adjust the regulatory system to accommodate reactors different from existing light water reactors.

REGULATORY CHALLENGES

The NRC plays a critical role in ensuring public safety and security, requiring careful, time-consuming, and independent analysis of a vendor's claims. An applicant frequently must have extensive interactions with the NRC as the staff ask detailed questions to understand the safety and security implications of a proposed new technology. The NRC confronts very significant challenges in the regulation of advanced reactors. Some of these challenges are discussed below.

Safety

The development of a new framework for licensing is only the start of the work. An applicant must offer detailed analyses, backed up by test data, to show that its design provides reasonable assurance of adequate protection of public health and safety. Some of the new designs offer potential advantages that could ultimately simplify licensing. As explained in Chapter 2, many of the designs have reactor cores with less radionuclide content (and hence a smaller accident source term per unit) and some contemplate the use of advanced fuels that fail at much higher temperatures than the fuel now used in LWRs. Other designs operate at near atmospheric pressure, which can offer safety advantages because they avoid the high-pressure operation necessary for LWRs, reducing the need for robust piping and pressure vessels and limiting the propulsion of debris and radionuclides in an accident. Similarly, many of the advanced designs rely on passive systems—that is systems that use gravity, natural convection, or pressure gradients to achieve safety objectives—rather than pumps, valve actuators, and AC power. If effective, these changes potentially offer significant safety advantages as well as a means to simplify the reactor design in ways that reduce cost.

Nonetheless, careful analyses and tests will be required to establish safety given some of the significant changes from existing LWRs. For example, some designs propose novel fuel forms or contemplate relaxation of siting requirements. A massive, reinforced concrete containment is a required feature of existing LWRs to provide a final barrier to the release of radionuclides to the environment in the event of an accident, but some advanced reactor vendors claim that their designs are sufficiently safe and the source terms sufficiently small that this requirement can and should be relaxed, with resulting significant cost savings. While existing LWRs are operated by staff located at the plant, some vendors

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[16] See Nuclear Regulatory Commission, 2020, "Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors," *Federal Register* 85(216):71002–71003. Staff has engaged in several rounds of interactions with the vendors and other stakeholders in the development of rule language.

[17] See Draft Statement of Considerations for Proposed Part 53 (NRC 2023).

argue that their designs will allow remote autonomous operation or at the least the reduction of staffing requirements. (NRC 2021b). These and many other such issues will have to be resolved through data and analysis in the safety review.

Microreactor designers seek to justify more significant modifications of the approaches to the assurance of safety than large reactors because of postulated lower risks.[18] The NRC staff has observed that tailored modifications may be required relating to security requirements, remote and autonomous operations, siting considerations, environmental review, regulatory oversight, staffing requirements, manufacturing licenses, and annual fees, among other licensing issues.[19] Again, a detailed review is necessary to justify any such adjustments of the regulatory requirements.

At the same time, the advanced reactors may present new challenges.[20] For example, sodium-cooled fast reactors will require consideration of sodium-water and sodium-air reactions that have plagued many past versions of this design. If sodium coolant chemistry is not properly controlled, it can be corrosive and has often resulted in leaks and fires. Molten salt reactors will also require careful consideration of corrosion and erosion issues and freezing of molten salt in piping. The regulator will have to consider whether the risks posed by these new fuels, coolants, moderators, and designs require additional safety and security measures.

Box 7-1 shows an illustrative list of the regulatory issues that may require or warrant adjustment of the requirements established for the current generation of large LWRs. The issues will certainly differ among the various types of advanced reactors, and not all the issues will necessarily arise in the review of a particular advanced reactor. Nonetheless, the list demonstrates the wide range of matters that may arise in the NRC's licensing review and that may require scrutiny. The NRC has undertaken considerable work to identify the matters with which it will be confronted and has interacted with vendors and other stakeholders to provide guidance as to how it plans to approach many of these matters.[21] But hard decisions remain ahead as the NRC actually resolves the many new matters in the review of licensing applications.

Even in those cases in which the requirements are not changed, the details of how to show compliance—that is, specifically how the requirements are met—are likely to be considerably different from those for conventional LWRs. As a result, the NRC will have to develop new review processes and/or acceptance criteria to ensure that an advanced design provides adequate public safety. That effort will involve a wide variety of challenges, particularly when it comes to the analytical modeling of various aspects of plant performance (including accident analyses). For example, the NRC may need to develop its own computer codes to allow it to review and independently verify an applicant's work. While the development of a risk-informed, performance-based licensing framework is likely to help focus the

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[18] Although there is not a precise agreed-upon term for what constitutes a micro reactor, such reactors are generally understood to have power levels generally on the order of tens of MWt or less (rather than the 3000 MWt output of large existing LWRs), low potential consequences from radiological releases, small site footprints, increased reliance on passive systems, and inherent characteristics to control power and heat removal.

[19] NRC, 2020, Policy and Licensing Considerations Related to Micro-reactors (SECY-20-093), https://www.nrc.gov/docs/ML2012/ML20129J985.pdf. See also NRC, 2021, Micro-reactors Licensing Strategies (staff white paper), https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML21235A418.

[20] The ACRS has observed:

> There is a tendency to believe in the perfection of new designs, especially when they are developed to eliminate the dominant failure scenarios in existing designs. However, one must remain vigilant and remember that nature provides surprises. There will be new accident scenarios and new combinations of events to be considered that challenge our expectations and our assumptions about these advanced reactor systems. Creative thinking will be required to identify such unique situations, to thoroughly identify the scenarios that will be the basis of the safety analysis and the source of releases, and to evaluate the suitability of sites.

Letter from P. C. Riccardella, ACRS Chairman, to Kristine Svinicki (October 7, 2019), https://www.nrc.gov/docs/ML1927/ML19277H031.pdf.

[21] The NRC webpage has a portal that provides access to the extensive work that has been undertaken by the staff to deal with the regulation of advanced reactors. https://www.nrc.gov/reactors/new-reactors/advanced.html.

NRC's effort, it is clear that the NRC staff has a major task ahead of it in dealing with novel features of an advanced reactor design or deployment strategy.

BOX 7-1
Illustrative Regulatory Matters for Advanced Reactors

Siting
- Adjustment of population density limitations
- Co-location with industrial facilities

Emergency planning zones
Offsite power
Defense in depth
Change control
Special treatment requirements for systems, structures and components
Fuel/core design/materials
- HALEU
- High burn-up fuels
- Metal alloy fuel
- TRISO fuel and variants
- Liquid fuel (for molten salt reactors)
- Advanced ceramic fuels (carbide, nitride, inert matrix)
- Thorium/U233 cycle
- U/Pu (MOX or metal) fuel
- Steel cladding
- Ceramic cladding
- Graphite
- Reprocessing/recycling
- Inventory management and accounting of liquid fuels
- Inventory management and accounting of pebble fuels

Fuel/core analysis
- Fuel element power limits
- Pebble-bed modeling
- Long-life cores

Reactor design/materials
- Advanced/high-temperature and high-dose alloys
- Shutdown cooling/decay heat removal systems
- In-reactor fuel handling systems

Reactivity control
- Control element design
- Self-actuated shutdown systems
- Diverse backup systems
- Criticality control for liquid fuel systems

Materials/structural analysis
- Stress/strain limits for advanced materials
- Creep
- Cyclic stress/strain
- Seismic analysis, including use of seismic isolation
- Sloshing loads
- Corrosion
- Code cases for advanced manufacturing/novel manufacturing processes

Accident analysis/consequences
- Sodium-water and sodium-air reactions
- Selection of design-basis accidents

- Verification/validation of non-LWR accident analysis codes
- Acceptance criteria for emergency core cooling systems
- Beyond-design-basis accident modeling

Containment design

- Criteria for functional containment
- Containment heat removal systems
- Use of filtered, vented containment

Secondary system designs

- Intermediate sodium systems
- Sodium/water leakage detection and handling of sodium-water reaction products

Plant design

- Direct cycle (gas-cooled reactors with Brayton cycle)
- Other non-Rankine cycle designs
- Shared systems in multi-modular plants
- Control room design criteria
- Reactor coolant level detection and cover gas monitoring (as applicable)
- Prevention of coolant freezing (sodium, molten salt)

Plant fabrication/construction

- QA rules for factory fabrication of modular/transportable reactors
- QA implementation and NRC inspection of factory-fabricated reactors
- Manufacturing licenses

Plant operations

- Remote operation
- Autonomous operation

Increased automation of operations
Artificial intelligence
Plant staffing
Waste handling

- On-line refueling and waste issues (e.g., pebble-bed, MSR online waste processing)
- Refueling operations in opaque (liquid metal) coolants
- Handling of radioactive/contaminated coolant materials (sodium, molten salt, etc.)
- Maintenance requirements for plants with long-lifetime cores
- Coolant purification (e.g., cold-trapping sodium), especially oxygen control

Security requirements, including both physical requirements and cybersecurity
Decommissioning

- Disposal of coolants that are mixed chemical and hazardous waste
- Storage and disposal of novel fuel forms

Other new risks

- Transportation of fully assembled and fueled reactors
- Transportation of irradiated modules
- Inventory management of liquid fuels or pebbles
- Multi-module risk assessment

The licensing of a novel design will likely also require that the NRC develop new expertise on technical issues with which the staff may not now have extensive experience, creating the potential for delay in regulatory decision-making. The NRC will have to buttress its current capabilities given the scope of the future challenges with which it is confronted. In awareness of the need for expanded knowledge and new skills, the NRC has provided staff with supplemental training and has made organizational changes to facilitate more efficient interactions with vendors. There are limitations on what can be accomplished, however, without a substantial investment to prepare for the expected set of new applications with which the staff will be confronted over the next several years. The NRC may be cautious in seeking significant additional resources as a result of its past experience in building a capacity to accommodate an expected "nuclear renaissance" that never occurred in the early years of this century.

NEIMA requires that most of the costs of NRC operations be recovered from fees paid by applicants and licensees, except for certain exempted activities. Congress provided an exemption from fees for activities relating to the development of regulatory infrastructure for advanced nuclear reactors, and the fiscal year (FY) 2022 budget provides $23 million that is exempt from fee recovery for this purpose.[22] But the excluded amounts do not cover expenses that can be attributed to specific projects and the NRC must develop the staff expertise and the tools to deal with specific advanced reactor technologies. Substantial efforts need to be undertaken now to prepare now for the anticipated applications, but it is inequitable to cover the costs from existing licensees (who may not benefit from this work), and some vendors may not have the financial depth to cover the costs, particularly in the period before they have a product to sell. Additional funds that are exempt from fees on the order of 10s of millions of dollars per year—a minimal investment in comparison with the federal funds that are being made available to develop advanced reactors—could enable the NRC to undertake the necessary preparations.[23]

Even more fundamental, is the need to undertake cultural change. The staff is accustomed to undertaking an extended review before accepting the deployment of unfamiliar technology. For example, it has taken considerable time for the NRC to review and accept new technologies in currently operating plants—such as the transformation from analog instruments to digital instrumentation and control. Cultural change is necessary to avoid needless delay and conservatism, while simultaneously enabling and encouraging thorough scrutiny in the review of advanced reactor applications. Cultural change could be the biggest challenge that now confronts the NRC. The NRC should retain its capability for thorough and careful review, while simultaneously streamlining its processes.

Finding 7-2: Establishing the safety case for an advanced reactor will require a thorough verification of the validity of safety claims based on detailed analyses founded on experimental data. All should recognize that the U.S. Nuclear Regulatory Commission will take its obligation to ensure adequate protection of public health, safety, and environment seriously and that the necessary thorough review of applications can be time consuming.

Recommendation 7-1: Advanced reactors will not be commercialized if the regulatory requirements are not adjusted to accommodate their many differences from existing light water reactors. A clear definition of the regulatory requirements for a new technology must be established promptly if timely deployment is to be achieved. The U.S. Nuclear Regulatory Commission (NRC) needs to enhance its capability to resolve the many issues with which it is and will be confronted. In recognition of the urgency for the NRC to prepare now, Congress should provide increased resources on the order of tens of millions of dollars per year to the NRC that are not drawn from fees paid by existing licensees and applicants.

Recommendation 7-2: The U.S. Nuclear Regulatory Commission should undertake a lessons-learned effort as it processes the first group of applications for advanced reactors as

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[22] Nuclear Regulatory Commission, 2022, "Revision of Fee Schedules; Fee Recovery for Fiscal Year 2022," *Federal Register* 87(36):10081–10107. The NRC's FY 2023 budget proposal for the regulation of advanced reactors is at roughly the same level ($23.8 million). See https://www.nrc.gov/docs/ML2208/ML22087A157.pdf.

[23] See Nuclear Innovation Alliance, 2021, Unlocking Advanced Nuclear Innovation: The Role of Fee Reform and Public Investment, Nuclear Innovation Alliance, Advanced Nuclear Energy Fee Reform Brief (July 2021), https://nuclearinnovationalliance.org/sites/default/files/2021-08/Advanced%20Nuclear%20Energy%20Fee%20Reform%20Brief.pdf.

a means to streamline its review without compromising its commitment to the public health, safety, and the environment.

Staged Investment

Although there is investor enthusiasm for advanced reactors, there is also considerable investment risk. There is the technical risk that an apparently promising technical approach proves on further review to have unanticipated vulnerabilities. There is market risk that a design may not prove attractive to customers because, for example, the hoped-for cost advantages are not realized. And there is regulatory risk because the NRC might reject a new approach or impose requirements that reduce a design's attractiveness. NRC review can also introduce costs and delays that are more than a vendor can bear. The regulatory risk may be particularly difficult for a vendor to evaluate because guidance from past NRC practice may not be available for a novel design. It must be remembered in this connection that Some of the vendors are comparatively small companies that may not have the financial capacity to survive under circumstances in which there are substantial and unanticipated front-end costs long before revenue from sales can be realized. Even well financed vendors may be discouraged by the costs.[24]

Investments in advanced technologies are typically made in stages or graduated steps so as to avoid unnecessary and often substantial front-end costs. That is, the investment may proceed in a stepwise fashion to reflect the retirement of risk, with subsequent investment made only as early hurdles are overcome. Ideally, major investment is postponed until after there is confidence that the design is on a plausible path to success. The existing regulatory approach can be inconsistent with this investment strategy because of substantial cost that must be incurred before DC, an OL or a COL is issued. As a result, NEIMA requires the NRC to establish stages in the licensing process for advanced nuclear reactors.

The NRC has sought to encourage interaction between staff and a vendor to identify difficult issues at an early stage. It encourages vendors to work with the staff to develop a licensing plan that reflects a common understanding of the responsibilities of each party and sets a licensing schedule. The NRC staff will use existing regulatory vehicles—technical reports, topical reports, exemption approvals, white papers, templates, and generic environmental impact statements—to provide early guidance to vendors as to how the staff would resolve issues. This accommodates the desire for staged licensing to some extent.

The use of these existing regulatory vehicles to provide early guidance does not fully resolve the desire for early retirement of regulatory issues because the staff does not have the final word. Final action involves not only the staff's recommendation for the issuance of a license (or DC), but also review by the Advisory Committee on Reactor Safeguards, possible litigation involving intervenors before the Atomic Safety and Licensing Board, review by the five-member Commission, and ultimately possible review in the courts. this review of the staff's work is a very important factor in providing the public with assurance of the thoroughness of the review and the validity of the NRC's final decisions. Thus, the resolution of issues by the staff may provide a vendor with significant comfort, but the staff's actions do not provide final resolution. But if each of the staff's intermediate decisions were to go through the necessary further review to bring those decisions to finality, there would be inevitable additional delay and cost in completing the licensing process.

Finding 7-3: There is a need to ensure a balance between staged licensing and efficiency in the licensing process. The existing process of providing intermediate, but non-final, resolution of matters by the U.S. Nuclear Regulatory Commission staff is a reasonable and practical compromise to provide timely and informed input to license applicants.

[24] As discussed in Chapter 3, various governmental initiatives are aimed at providing financial support in connection with matters that must be addressed in licensing.

International Harmonization

Many of the vendors clearly are hopeful of international sales. Indeed, given the anticipated efficiencies that may result from serial production, substantial foreign sales may be an essential part of their business plans. Some vendors hope, for example, that SMRs may be particularly attractive to developing countries because their cost should be more manageable than those of a Gwe-scale plant and the electrical output is more appropriate for small grids. SMRs also promise safety advantages, faster construction, and reduced operational costs. There is a danger, however, that adaptations or modifications may be needed to obtain licensing in each country in which a plant is sold, which could increase the cost of a plant and diminish international deployment.

Although efficiencies might be realized by establishing a transnational regulator, the current system of a network of national regulators will likely continue. National control over energy policy may be seen as so central to sovereignty that countries will demand continuing national regulatory control. Moreover, the affected population may require that the regulator be politically accountable and not reside in a foreign or transnational entity. And, of course, every regulator must accommodate local legal norms and societal expectations (Meserve 2009). Nonetheless, there are strong benefits from efforts to ensure that each regulator has access to the knowledge of others and that needless regulatory differences in approach and requirements are eliminated or at least reduced.

There are efforts to enhance international cooperation in ways that could lead to substantial harmonization in requirements. The NRC has bilateral arrangements with some 45 other nations that include technical exchanges, regulatory information sharing, temporary personnel exchanges, and assistance partnerships for regulatory program development (NRC 2022d), as well extensive international engagement through, for example, the International Atomic Energy Agency and Nuclear Energy Agency. The United States recently entered a Memorandum of Cooperation with Canada that is focused on a coordinated response to technical issues associated with the licensing of advanced reactors (CNSC 2022). Each country retains its regulatory authority, but coordination and communication can ensure that there is no duplication of effort or needless inconsistency in requirements.

The International Atomic Energy Agency is also making significant efforts to develop safety standards appropriate for advanced reactors and to allow a focused consideration of the appropriate regulatory regime through its SMR Regulators' Forum. These activities involve regulators from around the globe and should serve, over time, to encourage consensus approaches. Moreover, the Nuclear Energy Agency has a similar effort under way, and its Multinational Design Evaluation Project, by which countries that are licensing a particular reactor coordinate their efforts, provides a model for harmonization of requirements for advanced reactors.

The aviation industry may also provide a model for international harmonization. Safety has been greatly enhanced in the past several decades in the aircraft industry, as indicated by a significant decrease in the fatal accident rate. National aviation regulators have the same degree of authority and responsibility as their peers in nuclear regulation. But the coordination among regulators is more effective, thereby allowing aircraft to cross national borders. The worldwide framework for aviation regulation is governed by the 1944 Convention on International Civil Aviation (the Chicago Convention) and the International Civil Aviation Organization (ICAO). It does not involve the transfer of responsibilities from national regulators, but it sets a framework for each regulator to fully discharge its duties, encouraging standardization and harmonization of the design approval and change management procedures. Perhaps the role of the IAEA standards could be strengthened so the IAEA can play a role like that of ICAO in supporting harmonization of aviation requirements, while allowing individual nations to maintain sovereignty. Several reports have examined this paradigm and additional review and development of the concept is warranted to determine if it may accelerate deployment of the technology while limiting safety risk (NEA 2022; WNA 2013).

In light of the importance of international markets, significant efforts should be undertaken now to reconcile needless differences in licensing obligations. At the same time, as discussed in Chapter 10, there is a need to develop a robust regulatory capability and infrastructure among those countries that lack that capability today. The necessary concerted international effort to build capacity in these countries should serve to encourage the harmonization of regulatory standards.

Finding 7-4: International sales may be an essential part of the business plans of some vendors. Regulatory requirements that differ from country to country can inhibit international sales.

Recommendation 7-3: In light of the importance of international markets, significant efforts should be undertaken now to reconcile needless differences in licensing obligations from one country to another. This should involve increased engagement with the International Atomic Energy Agency and the Nuclear Energy Agency on these matters, as well as exploration of regulatory mechanisms like those used by the aviation industry. In the meantime, bilateral arrangements with other countries pursuing advanced reactors, such as the memorandum of understanding that the United States has entered with Canada, may pave the way for broader international harmonization.

Siting and Emergency Planning Zones

One of the aspects of the safety review that bears significantly on the business plans of the vendors concerns proposed modification in the requirements for siting and emergency planning zones (EPZs). Existing domestic nuclear plants have extensive owner-controlled areas, and their locations were selected to comply with siting requirements relating to the population density in the vicinity, typically within a 20-mile radius from the plant, as well as limitations on siting within the vicinity of large population centers. The NRC also has separate requirements for EPZs to control exposures to a radioactive plume arising from an accident, typically to a distance of 10 miles, and to control ingestion out to a distance of 50 miles (see Box 7-2). The vendors of some advanced reactors argue that their designs justify relaxation of these siting and EPZ requirements. They assert that their designs are sufficiently safe and/or that the consequences of an accident are sufficiently small or slow to develop that a modification of the current siting and EPZ requirements can be justified. Indeed, such relaxation would be absolutely essential if some of the proposed uses of the reactors are to be realized. For example, some of the vendors anticipate providing process heat for industrial applications, which requires the reactor to be in the vicinity of the industrial facility. The use of heat from an NPP at a nearby industrial site presents a regulatory complication because it requires the evaluation not only of the risk posed at the industrial site, but also the risk to the nuclear plant from the nearby facility.[25] Some vendors contemplate that their designs might be deployed as replacements for similarly sized fossil plants, thereby benefiting from existing infrastructure, transmission capabilities, skilled workforce, and nearby cooling water.[26] Siting considerations will arise in repowering fossil plants that are near to or in the middle of populated areas (Hansen 2022). Some of the proponents of microreactors claim that the risks are so small that they may be placed in middle of urban areas to provide power to microgrids or to power vehicle charging stations.

Careful and early determination of the appropriate siting and EPZ requirements is necessary to define the range of siting opportunities that are available for advanced reactors. The NRC is pursuing the modification of these requirements in light of the lesser risks that are postulated for some advanced reactors. Consideration and early revision, if appropriate, of these requirements is essential for defining the prospects for novel applications of advanced reactors.

[25] As a part of its existing requirements, the staff reviews manufacturing, processing and storage facilities within 5 miles of a reactor to assess potential hazardous activities that could cause damage. Facilities and activities at distances greater than 5 miles are considered if they have the potential for affecting plant safety-related features. NRC, Standard Review Plan, § 2.2.1–2.2.2 (Identification of potential hazards in site vicinity) (NUREG-0800).

[26] The replacement of coal plants by nuclear plants is encouraged by the IRA through tax incentives.

BOX 7-2
Current Siting Guidance

The current siting requirements are specified in10 CFR 100.21. They include two zones: an *exclusion area* subject to the owner's control and a *low population zone* (LPZ), which consists of the area immediately surrounding the exclusion area in which the total number and density of population is such that there is a reasonable probability that appropriate protective measures could be taken in the event of a serious accident. Current regulatory guidance calls for the population to be less than about 1,600 people within a mile from the plant site, for the total population within the first 10 miles to be less than about 157,000 people and less than about 628,000 people within 20 miles from the site. NRC Reg. Guide 4.7, rev. 3 (March 2014). In addition, the reactor should be sited away from densely populated centers. A population center distance is defined as the distance from the reactor to the nearest boundary of a densely populated center of more than about 25,000 residents; the population center distance must be at least 1.33 times the distance from the reactor to the outer boundary of the LPZ. 10 CFR 100.21(h) provides that in analyzing a site located away from a very densely populated center but not in an area of low density, consideration will be given to safety, environmental, economic, or other factors, which may result in the site being found acceptable.

In recognition that these requirements may not be appropriate for some advanced reactors, the NRC staff proposed various options for their modification. In July 2022 the Commission directed the staff to develop guidance for a dose-based approach to define the siting requirements. The revised approach opens the possibility that the siting requirements might be significantly relaxed in appropriate cases from the existing guidance. A dose analysis might allow, for example, for the exclusion zone and the low population zone to be reduced to the site boundary and the allowed distance from a population center to be determined based on a dose analysis. Specifics are found in NRC, SECY-20-1045, Population-Related Siting Considerations for Advanced Reactors (May 8, 2020). Formal guidance remains to be developed and its implementation will require detailed calculations to determine the siting restrictions for a given advanced reactor design.

Part 50 requires that each reactor license applicant provide plans for coping with emergencies by establishing EPZs. 10 CFR 50.4I) (2) provides that "[g]enerally, the plume exposure pathway EPZ for nuclear power plants shall consist of an area of about 10 miles (16 km) in radius and the ingestion pathway EPZ shall consist of an area of about 50 miles (80 km) in radius." The distances were determined from technical analyses for conventional LWRs and may not be appropriate for many advanced reactors. *See* NUREG-0396 (December 1978); NUREG-0654 Rev 2 (December 2019). The NRC staff has recently prepared a final rule for the Commission's consideration that, among other things, proposes a modified approach to determine the plume exposure EPZ for advanced reactors. The EPZ would be defined as the area in which the public dose is projected to exceed certain dose limits (10 millisieverts total effective dose equivalent over 96 hours) from the release of radioactive materials resulting from a spectrum of credible accidents. NRC, Final Rule: Emergency Preparedness for Small Modular Reactors and Other New Technologies (2022) (SECY-22-0001). This of course means that different advanced reactors could have different EPZs. Several of the reactor vendors contend that a modified approach could serve to reduce the EPZ for their design to the site boundary.

Finding 7-5: Some reactor vendors anticipate opportunities to deploy their reactors near or in urban environments or in the vicinity of industrial facilities that will use heat produced by the reactor. These applications of advanced reactors will present unique siting and emergency planning issues. Careful and early examination of such issues is necessary to define the future range of economic opportunities that are available for advanced reactors.

Recommendation 7-4: The U.S. Nuclear Regulatory Commission should expedite the requirements and guidance governing siting and emergency planning zones to enable vendors to determine the restrictions that will govern the deployment of their reactors.

Security

As discussed in depth in Chapter 9, the current physical security framework constitutes prescriptive regulatory requirements for large LWRs that have been augmented over time as the terrorist threat has grown. See 10 CFR Part 73. Some advanced reactors are expected to include attributes that result in smaller or slower release of radionuclides as well as inherent safety characteristics and simplified safety systems that may be less reliant on physical security systems and procedures for protection against sabotage than current generation plants. (NRC 2018b; NEI 2016). Moreover, most existing reactors were not designed with security requirements as a primary concern. There is thus the opportunity and the need to incorporate security considerations in the basic design of the plant—"security by design"—providing the opportunity to improve security and perhaps reduce reliance on security personnel, which constitute a meaningful part of the operating cost at existing reactors.[27] The possible improvements include, for example, reduction in the number of vital areas subject to sabotage and to locate them so they are easier to defend, to establish fighting positions with overlapping fields of fire and hardened defensive positions, to provide for nested security layers and more opportunity for delay (Duguay 2020). But in order to achieve these aims, some modification of the existing security requirements is required. Indeed, some vendors of microreactors claim that the risks are so slight that operation might proceed without a security force or even without operators of any kind.

As discussed in Chapter 9, the NRC staff has sought authorization from the Commission to publish a proposed rule that would offer voluntary performance-based alternatives for meeting certain of the physical security requirements for advanced reactors.[28] At the same time, the heightened concern for cybersecurity means that the careful consideration of the associated regulatory requirements is essential for advanced reactors, particularly because many intend to place much greater emphasis on digital systems and automated intelligence than existing reactors. Chapter 9 includes findings and recommendations bearing on the NRC's approach to these security requirements.

Transportable Reactors

Some vendors are exploring the possibility of reactors in one location and then transporting them by truck, rail, or a barge to a site for deployment. Building a reactor on a barge or platform and installing it offshore to provide power to meet local onshore demand is also under consideration (Stauffer 2015). Nuclear reactors might also be used as a power source on ships to meet the needs of maritime commercial shipping.[29]

Small reactors or microreactors can be designed to be mobile and moved from place to place to serve a remote location or to meet emergency needs.[30] Indeed, some analysts suggest that our energy infrastructure should be transformed to depend on widespread deployment of microreactors to provide power to microgrids collocated with end users (Buongiorno et al. 2021).

These applications present some novel regulatory issues, particularly if the factory construction and transport of fueled reactors is contemplated. As noted above, existing regulations would require

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[27] Safety and security need to be considered together so as to ensur43e that both purposes are served appropriately. See International Nuclear Safety Group, 2010, The Interface Between Safety and Security at Nuclear Power Plants (INSAG-24).

[28] U.S. Nuclear Regulatory Commission, 2018, "SCY-18-0076: Options and Recommendations for Physical Security for Advanced Reactors," https://www.nrc.gov/docs/ML1817/ML18170A051.html. *See also* Nuclear Energy Institute, 2021, Methodological Approach and Considerations for a Technical Analysis to Demonstrate Compliance with the Performance Criteria of 10 CFR 73.55(a)(7), Draft A, https://downloads.regulations.gov/NRC-2017-0227-0027/content.pdf.

[29] NRIC is providing funding to the American Bureau of Shipping to research barriers to the adoption of advanced nuclear propulsion on commercial vessels (WNN 2022).

[30] As discussed in chapter 4, the Department of Defense is pursuing the development of small mobile reactors to meet its needs (Project Pele).

additional licenses for fuel loading at the factory, for test operation at the factory, for transport of a fueled reactor to a site, and for transport back to the factory for refueling. Unique safety and security issues will arise in the transport of a fueled reactor, just as they arise in the transport of fresh and spent fuel. (Maheras 2020).

As discussed in Chapter 10, the situation becomes even more complex if the reactor is fabricated in one country and then transported to another country for operation. In such a case there will likely be a complicated legal relationship among the supplier country and its regulator, the host country and its regulator, the vendor, and the operator, most notably with regard to nuclear liability and the governmental, legal, and regulatory framework for safety.[31] A pathway for the resolution of these thorny regulatory issues must be established if these opportunities are to be realized.

Decommissioning

NRC requirements cover decommissioning of a nuclear facility to remove it safely from service and to reduce residual radioactivity to a permissible level. (See 10 CFR Part 20, Subpart E, and 10 CFR 50.75, 50.82, 51.53, and 51.95.) Some advanced reactors may present unique decommissioning challenges at the end of their useful life. Examples may include disposal of coolants that need to be treated as mixed chemical and radioactive waste (e.g., sodium or molten salts) or handling the dust accumulation in pebble bed reactors. Moreover, the storage and disposal of the unique fuels proposed for some designs may present new challenges beyond the formidable difficulty of disposing of conventional LWR fuel.[32] Just as vendors should consider safety, safeguards, and security in the design of their plants, consideration should be given to facilitating decommissioning at the end of a reactor's life. Lessons may be learned from the extensive DOE and DOD activities in decommissioning nuclear facilities,[33] as well as from the decommissioning of commercial and research reactors.

> Finding 7-6: Some advanced reactors are likely to present unique and difficult decommissioning challenges.
>
> **Recommendation 7-5: Reactor developers need to consider the challenges associated with decommissioning and address them in the reactor design. The failure to consider decommissioning issues in the design phase could result in large expenses at the end of a reactor's life. Vendors should exploit the lessons learned from Department of Energy and Department of Defense decommissioning activities, as well as from the decommissioning of power and research reactors.**

Fuels

Fuel types that differ from those used in existing LWRs are proposed for some advanced reactors. These include tristructural isotropic (TRISO) particle fuels, metallic fuels, and liquid molten salt fuels, in many cases with enrichments of nearly 20 percent ^{235}U. The NRC requires that all fuels meet regulatory requirements under conditions of normal operation, anticipated operational occurrences (AOOs), and accident conditions. In the case of some advanced reactors, consideration must be given to an operating

[31] See IAEA, 2013, Legal and Institutional Issues of Transportable Nuclear Power Plants: A Preliminary Study (NG-T-3.5). Complicated regulatory requirements would likely be associated with reactors used for propulsion for commercial shipping (e.g., unique inspection requirements at every port for a nuclear vessel landing to load/offload).

[32] For more information on fuel cycles for new and advanced reactors, see NASEM, 2022, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*, Washington, DC: The National Academies Press, https://doi.org/10.17226/26500.

[33] See Deactivation and Decommissioning Knowledge Management Tool, 2018, https://www.dndkm.org/LessonsLearned/SearchLessonsLearned.aspx?Query=ProjectManagement.

environment that will differs from that of an LWR—for example, different neutron energy spectra, fuel temperatures, cladding-coolant compatibility, and retention of fission products (NRC 2022a). There may be limited experimental and operational data on some of the proposed fuel types, which is likely to pose a particular challenge for some designs because of the need for extensive irradiation to provide the data necessary to support the safety case (NRC 2022b). At the same time, the production of some of the novel fuels will require the development of new fuel cycle infrastructure, presenting serious economic, regulatory, and policy challenges. Some of these matters are discussed in the companion study to this report (NASEM 2022). They are mentioned here because the challenges of ensuring fuel availability and fuel safety are likely to be pacing items for the deployment of some advanced reactor designs and they raise significant regulatory issues.

> Finding 7-7: Some vendors propose to use novel fuels for which limited experimental or operational data is available. This is likely to present a particular regulatory challenge because of the need for extended fuel irradiation to provide the data necessary to support the safety case for the designs. Moreover, the development of the necessary fuel cycle infrastructure will require extensive new regulatory activity.

In sum, there are many difficult matters that must be resolved in the licensing of advanced reactors. Significant efforts are under way in the United States involving the generating companies, the vendors, DOE, various stakeholders, and the NRC to confront these challenges. But their early resolution is essential if timely deployment of non-LWR advanced designs presenting regulatory issues is to occur.

REFERENCES

Buongiorno, J., R. Freda, S. Aumeier, and K. Chilton. 2021. A Strategy to Unlock the Potential of Nuclear Energy for a New and Resilient Global Energy-Industrial Paradigm. *The Bridge* 51(2). Washington, DC: National Academy of Engineering.

DOE-NE (Department of Energy Office of Nuclear Energy). 2019. "ANALYSIS: FY2020 Spending Bill Points to Nuclear Resurgence." https://www.energy.gov/ne/articles/analysis-fy2020-spending-bill-points-nuclear-resurgence.

DOE-NE. 2020. *Request for Information/Notice of Intent, DE-FOA RFI-0002271, Information Request on the Advanced Reactor Demonstration Program*. https://beta.sam.gov/opp/badc601a2cd74208a0d15a6a08ca6d0d/view.

Duguay, R. 2020. "Small Modular Reactors and Advanced Reactor Security: Regulatory Perspectives on Integrating Physical and Cyber Security by Design to Protect Against Malicious Acts and Evolving Threats." *International Journal of Nuclear Security* 7(1):Article 2. https://doi.org/10.7290/ijns070102.

GNI (Global Nexus Initiative). 2019. *Advancing Nuclear Innovation: Responding to Climate Change and Strengthening Global Security*. Washington, DC: Nuclear Energy Institute and Partnership for Global Security. https://globalnexusinitiative.org/results/reports/advancing-nuclear-innovation-responding-to-climate-change-and-strengthening-global-security.

INSAG (International Nuclear Safety Advisory Group). 2019. *Basic Safety Principles for Nuclear Power Plants 75-INSAG-3 Rev. 1*. INSAG-12. Vienna: International Nuclear Safety Advisory Group.

Kadambi, N.P., E. Wallace, J. O'Brien, and R. Youngblood. 2020. "Risk-Informed, Performance-Based Safety: Past, Present, and Future." *Nuclear Newswire*, June 26, 2020. https://www.ans.org/news/article-300/ri-pb.

Maheras, S.J. 2020. *Environmental Impacts from Transportation of Fuel and Wastes to and from Non-LWRs*. PNNL-29365. Richland, WA: Pacific Northwest National Laboratory.

Meserve, R.A. 2009. "The Global Nuclear Safety Regime." *Daedalus* 138(4):100–111. http://www.jstor.org/stable/40544005.

Meserve, R.A. 2020. "Regulatory Innovations to Support Advanced Reactors." *The Bridge* 50(3):54–60. Washington, DC: National Academy of Engineering.
MIT (Massachusetts Institute of Technology). 2018. *The Future of Energy in a Carbon-Constrained World: An Interdisciplinary MIT Study*. Cambridge, MA: Massachusetts Institute of Technology.
NASEM (National Academies of Sciences, Engineering, and Medicine). 2022. *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.
NEI (Nuclear Energy Institute). 2016. *Proposed Physical Security Requirements for Advanced Reactor Technologies.* Nuclear Energy Institute. https://www.nrc.gov/docs/ML1702/ML17026A474.pdf.
NEI. 2019. *Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development.* NEI 18-04 Rev 1. Nuclear Energy Institute. https://www.nrc.gov/docs/ML1924/ML19241A472.pdf.
NEIMA (Nuclear Energy Innovation and Modernization Act). 2019. Public Law 15-439, 132 Stat. 5565. https://www.congress.gov/bill/115th-congress/senate-bill/512/text.
NRC (U.S. Nuclear Regulatory Commission). 1986. "Safety Goals for the Operation of Nuclear Power Plants; Policy Statement" *Federal Register* 51(149):28044–28049.
NRC. 1995. "Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities; Final Policy Statement." *Federal Register* 60(158):42622–42629.
NRC. 2007. *Feasibility Study for Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing*. NUREG-1860. Washington, DC: Nuclear Regulatory Commission.
NRC. 2016a. "Variable Annual Fee Structure for Small Modular Reactors (Final Rule)." *Federal Register* 81(100):32617–32628.
NRC. 2016b. "Accident Source Terms and Siting for Small Modular Reactors and Non-Light Water Reactors." SECY 16-0012. https://www.nrc.gov/docs/ML1530/ML15309A319.pdf.
NRC. 2017a. *A Regulatory Review Roadmap For Non-Light Water Reactors*. ML17312B567. Nuclear Regulatory Commission.
NRC. 2017b. *Siting Considerations Related to Population for Small Modular and Non-Light Water Reactors (Preliminary Draft)*. https://www.nrc.gov/docs/ML1733/ML17333B158.pdf.
NRC. 2018a. "Backgrounder on Nuclear Power Plant Licensing Process." https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/licensing-process-fs.html.
NRC. 2018b. "Options and Recommendations for Physical Security for Advanced Reactors." SECY 18-0076. https://www.nrc.gov/docs/ML1805/ML18052B032.pdf.
NRC. 2018c. "Functional Containment Performance Criteria for Non-Light-Water Reactors." SECY 18-0096. https://www.nrc.gov/docs/ML1811/ML18115A157.pdf.
NRC. 2019a. *Non-Light Water Review Strategy (Draft Staff White Paper)*. https://www.nrc.gov/docs/ML1927/ML19275F299.pdf.
NRC. 2019b. "Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content to Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors." SECY-19-0117. https://www.nrc.gov/docs/ML1831/ML18311A264.html.
NRC. 2019c. *Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content for Applications for License, Certifications, and Approvals for Non-Light-Water Reactors (Draft Reg. Guide DG-1353)*. https://www.nrc.gov/docs/ML1831/ML18312A242.pdf.
NRC. 2019d. "Chapter 8: Electric Power." In *NuScale DCA Advanced Safety Evaluation Reports with Open Items (Review Phase 2)*. ML19191A196. https://www.nrc.gov/docs/ML1806/ML18060A144.pdf.
NRC. 2019e. "In the Matter of Tennessee Valley Authority (Clinch River Nuclear Site Early Site Permit Application)." CLI-19-10. https://www.nrc.gov/docs/ML1935/ML19351D663.pdf.
NRC. 2019f. Physical Security for Advanced Reactors (Basis for a Proposed Rule). *Federal Register* 84(136):33861–33864. https://www.federalregister.gov/documents/2019/07/16/2019-15008/physical-security-for-advanced-reactors.

NRC. 2019g. *Functional Containment Performance Criteria Technology-Inclusive, Risk-Informed, Performance-Based Approach*. ML18115A367—SECY 19-0096. Nuclear Regulatory Commission.

NRC. 2019h. *Approaches for Expediting and Establishing Stages in the Licensing Process for Commercial Advanced Nuclear Reactors*. ML19128A319—Enclosure 1. Nuclear Regulatory Commission.

NRC. 2019i. *Increasing the Use of Risk-Informed and Performance-Based Evaluation Techniques and Regulatory Guidance in Licensing Commercial Advanced Nuclear Reactors*. ML19128A324—Enclosure 2. Nuclear Regulatory Commission.

NRC. 2020a. New Reactors Business Line Fee Estimates. https://www.nrc.gov/reactors/new-reactors/new-licensing-files/nro-fee-transformation-data.pdf.

NRC. 2020b. *Non-Light-Water Reactor Implementation Action Plan—Progress Summary and Future Plans*. ML19331A712—SECY 20-0010 Enc. https://www.nrc.gov/docs/ML1834/ML18346A181.pdf.

NRC. 2021. “History of NRC’s Risk-Informed Regulatory Programs.” https://www.nrc.gov/about-nrc/regulatory/risk-informed/history.html.

NRC. 2021a. *Completing a Rulemaking to Establish a Technology-Inclusive Regulatory Framework for Optional Use by Commercial Advanced Nuclear Reactor Technologies in New Reactor License Applications and to Enhance Commission Expertise relating to Advanced Nuclear Reactor Technologies*. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML2110/ML21109A261.pdf.

NRC. 2021b. Ground Rules for Regulatory Feasibility of Remote Operations of Nuclear Power Plants. https://www.nrc.gov/docs/ML2129/ML21291A024.pdf.

NRC. 2022a. *Fuel Qualification for Advanced Reactors*. NUREG-2246. Nuclear Regulatory Commission.

NRC. 2022b. *Nuclear Data Assessment for Advanced Reactors*. NUREG/CR-7289, ORNL/TM-2021/2002. Nuclear Regulatory Commission.

NRC. 2022c. “NRC Denies Oklo Combined License Application.” *NRC News*, January 6. https://www.nrc.gov/reading-rm/doc-collections/news/2022/22-002.pdf.

NRC. 2022d. “Bilateral Relations.” https://www.nrc.gov/about-nrc/ip/bilateral-relations.html

NRC. 2023. “Part 53—Risk-informed, technology inclusive regulatory framework for advanced reactors.” https://www.nrc.gov/reactors/new-reactors/advanced/rulemaking-and-guidance/part-53.html.

NRC Staff. 2021. *Micro-Reactors Licensing Strategies*. Nuclear Regulatory Commission. https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML21235A418.

SEAB (Secretary of Energy Advisory Board). 2016. *Report of the Task Force on the Future of Nuclear Power*. https://www.energy.gov/seab/downloads/final-report-task-force-future-nuclear-power.

Walker, J.S., and T.R. Wellock. 2010. “A Short History of Nuclear Regulation, 1946–2009, Rev. 2 (NUREG/BR-0175).” https://www.nrc.gov/reading-rm/doc-collections/nuregs/brochures/br0175.

8

The Social Acceptance Challenge

Public opposition to nuclear power ranks among the most salient challenges impeding the construction of new nuclear power plants (NPPs); it has persisted despite decades of research into underlying attitudes toward the technology and has proven to be a difficult task for the industry to address. Like achieving cost control and ensuring high levels of regulatory quality, overcoming the social acceptance challenge is a necessary but insufficient condition if new reactors are to play an expanded role in decarbonizing the global energy system.

Understanding public attitudes toward nuclear power rests to a great extent outside engineering: the determinants of those attitudes involve economic, social, behavioral, and political realities—many of which are exogenous to the industry. This is not to diminish the role of the industry's experts in addressing the challenge: social acceptance can increase or decrease based on the technical and risk communication decisions made by experts within the industry.

The purpose of this chapter is to outline the underlying roots of nuclear power's social acceptance challenge and provide guidance on how to address it if the technology is to play an expanded role in the future energy system. It will begin by framing the challenge—why does social acceptance matter? It will then list the underlying roots of social opposition to nuclear power. This section will necessarily adopt a historical perspective, but it is important to stress three facts. First, only some of these underlying roots are specific to nuclear; others could impede (indeed, have impeded) the deployment of other infrastructure, both energy-related and otherwise. Second, the strength of public opposition and the role in shaping it varies across space and time. This chapter references academic literature that has analyzed different publics; it would be inappropriate to generalize the results of these studies to the United States (or world) without further research. Third, public attitudes do not necessarily always harden—they could change.

The ultimate focus of this chapter will be to review the strategies that the industry has used in the past to address the social acceptance challenge, outlining their limitations, and providing a roadmap—a set of principles or best practices—for good community engagement. These cover elements of the reactor development process as disparate as research, design, siting, and engineering education. This will drive most of its findings and recommendations, which are derived not only from the academic literature (in the fields of the social and decision sciences and science and technology studies) but also from a workshop organized by the committee. The proceedings of this workshop was reviewed and published by the National Academies (NASEM 2022b).

WHY DOES SOCIAL ACCEPTANCE MATTER?

Poor social acceptance limits the diffusion of promising technologies, including nuclear power, in more ways than one. First and foremost, it makes the siting of facilities a potentially contentious or difficult process. Overcoming that opposition during the siting phase, whether through sustained community engagement or direct action, incurs economic and political costs—often at a moment in time when the project is especially vulnerable. In the case of nuclear power and in the absence of an offsite waste repository, securing a social license to operate is even more important, because communities being asked to host new power plants might then host their spent fuel for substantial periods of time. This study does not discuss the nuclear fuel cycle upstream or downstream of the reactor plant. However, to provide valuable context, Box 8-1 summarizes the social opposition faced by the Yucca Mountain nuclear waste repository since it was proposed in the mid-1980s. Last, the consequences for a technology of acquiring a reputation as controversial or difficult can reverberate across financial markets, making both public and private investment more difficult to secure. Conversely, technologies that are socially acceptable can more readily attract such investment. Social acceptance can therefore impact the fortunes of a technology.

It is impossible to develop a nuclear energy system that would gain universal approval, nor should that be the industry's goal. Some communities and polities would never agree to the deployment of an NPP. Instead, the goal should be to acknowledge the underlying roots of concerns, and to deploy reactors in a fashion that addresses them. Scientists and engineers optimize their engineered systems for technical performance or least-cost, often ignoring the non-technical challenges that constrain adoption. However, the energy transition is not a technical transition; it is a socio-technical transition and integrating the public's attitudes and behaviors into engineering assessments is crucial to develop truly sustainable technologies—ones that are both techno-economically feasible and socio-politically acceptable.

Finding 8-1: A successful deployment of advanced nuclear energy will require technologies that meet a specific market need at an economic price and that integrate safety, safeguards, and security into the design. Far less appreciated, but likely as critical, is the need to integrate public participation and consent into design, siting, and long-term operations.

Recommendation 8-1: Socio-technical approaches should become part of the nuclear energy research and development (R&D) cycle, treated with the same seriousness as technological development. Research programs need to be reimagined to include public engagement starting at early innovation and through planning, design, deployment, and operation. These programs should be endogenous to the R&D cycle (rather than added on) and should be taken seriously and done rigorously. The Department of Energy should update its programs and associated budget requests to include social science along with their traditional physical science and engineering research. This should lead to the establishment and support of a national cohort of scholars leading in the socio-technical aspects of nuclear energy use.

BOX 8-1
Public Opposition to the Yucca Mountain Nuclear Waste Repository

Yucca Mountain, Nevada, is a proposed geological repository for spent nuclear fuel and high-level radioactive waste. Although the Act required DOE to begin accepting spent fuel in 1998, this never came to fruition. Since 1987, the state of Nevada has consistently opposed the repository and created numerous legal hurdles, including lawsuits and denial of water rights, and community support oscillated. Two-thirds of Nevadans do not think waste storage belongs in their state, particularly because the state has no NPPs. Furthermore, the Western Shoshone peoples contested the project, citing it as a form of environmental racism that did not acknowledge the cultural significance of their land, nor their safety concerns about radiation and seismicity. The potential Yucca Mountain repository remains entrenched in political limbo, and most spent fuel in the United States is kept on-site at NPPs in spent fuel pools and dry cask storage.

In contrast, the Waste Isolation Pilot Plant (WIPP) in New Mexico enjoys broad support from the local community and is the world's only operating deep geologic repository for nuclear waste disposal, as of 2022. The low- and intermediate-level waste shipped to WIPP is limited by statute to that generated by defense activities. WIPP constitutes a success in the siting of nuclear facilities: combined with other repositories under construction in the Nordic countries, it demonstrates that siting nuclear facilities is possible with robust community engagement that is open and transparent. If siting nuclear *waste* facilities—which are permanent—can succeed, then siting new nuclear *power* facilities is surely possible if best practices for societal engagement are internalized by industry and government.

THE UNDERLYING ROOTS OF PUBLIC OPPOSITION TO NUCLEAR POWER

The underlying roots of public opposition to nuclear power are complex. Almost any new activity or technology may stimulate at least some form of public opposition, and only some are inherent to the technology. Some are more deep-rooted than others; and some are rooted in how people perceive risks and benefits. Nuclear power has been the subject of extensive public polling, including in the United States, and a substantial literature in the social sciences exists that extracts and analyzes the attitudes of different publics toward the technology. This has been done both in the abstract and with respect to different facilities such as power reactors and waste repositories.

Public Opinion Polls

Rigorously eliciting the roots of public attitudes toward nuclear power requires careful social and decision science, and the importance of good experimental design cannot be understated. Nonetheless, the focus is on public opinion polls first. When done reliably and frequently, polling gives a general impression of how a community feels about a subject but rarely delves deeper than that. For example, why is this general impression held? Is it held strongly, or is it mutable? In the case of nuclear power, polls rarely extract the determinants of these impressions. In fact, patterns in public opinion often shift; the key is to maintain an approach to public engagement that follows the best practices that are discussed at the conclusion of this chapter. Moreover, high levels of support for a hypothetical plant do not necessarily translate into easier siting decisions.

In the United States, although the first commercial nuclear reactor in the United States was synchronized to the power grid in 1958, the technology remained psychologically distant from the public until builds commenced in earnest during the Great Bandwagon Market of the 1960s and 1970s. Protests began to be held, some of which were covered on national news outlets (OTA 1984, p. 211). Despite these protests, surveys only began explicitly asking the public for their opinion regarding nuclear energy in the mid-1970s. Those early polls suggested that the American public was either supportive of or ambivalent toward nuclear power, with organized opposition emerging among civil society and environmental groups. In the early years of the atomic age, the debate regarding the role of nuclear power in the energy system was impacted by the larger context of the Cold War, and by the role that nuclear weapons played in both that conflict and in the birth of nuclear science and technology. In other words, some of the opposition to nuclear power emanated from the same segments of the population that were supportive of nuclear disarmament.

By the mid-1970s at the latest, wiser and more forward-thinking members of the U.S. nuclear community had become cognizant of the degree to which broad public opposition was constraining further nuclear development. In 1976, Alvin Weinberg stated,

> As I compare the issues we perceived during the infancy of nuclear energy with those that have emerged during its maturity, the public perception and acceptance of nuclear energy appears to be the question that we missed rather badly.… This issue has emerged as the most critical question concerning the future of nuclear energy. (p. 19)

Opposition to nuclear reactor builds in the United States increased after the Three Mile Island Accident in March 1979; it also increased after the Chernobyl accident of 1986. In each case, after a substantial period (several years) had passed, public opinion polls suggested that attitudes among the public settled back at levels of general ambivalence, with no evident majority (or, arguably, plurality) of respondents supporting or opposing the technology. The same happened after Fukushima in March 2011: opposition increased initially but by 2019 Americans were evenly split on the topic of nuclear energy. Figure 8-1 summarizes results from polls conducted over the past four decades.

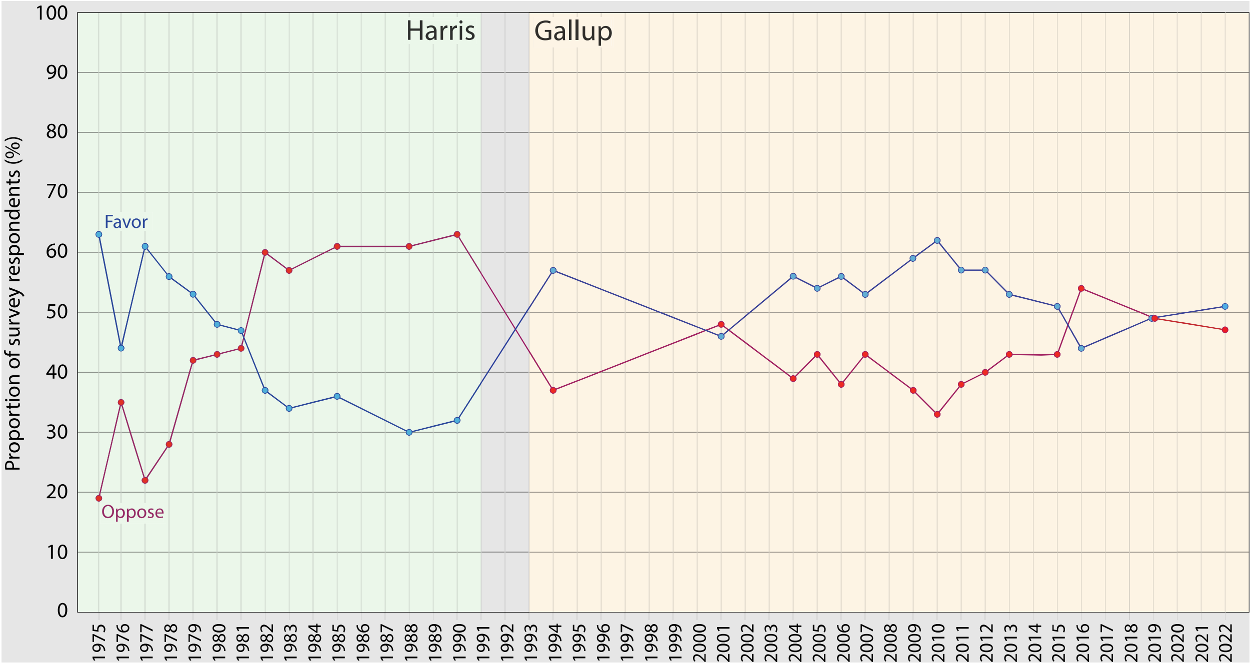

FIGURE 8-1 Various reputable public opinion polling outfits have been surveying the U.S. public's attitudes to nuclear energy since the 1970s. After Three Mile Island in 1979, polls were conducted almost monthly well into 1980: results are averaged for ease of presentation.
SOURCE: Committee generated from Gallup, 2022. "America is Divided on Nuclear Energy." https://news.gallup.com/poll/392831/americans-divided-nuclear-energy.aspx

The schism in attitudes toward nuclear power in the United States emerged in John Kemeny's account of the lessons he learned while chairing the Commission on the Accident at Three Mile Island (Kemeny 1980). Kemeny identified a litany of "people problems": among these are problems that the next section will discuss at length: the attitudes of technical experts; the difficulty of contending with deep uncertainty; the media's treatment of scientific topics; and how institutions respond to large and complex challenges.

The one poll that consistently reveals support for nuclear power is the industry's own. The Nuclear Energy Institute and the American Nuclear Society commission their own polls. With one exception (around the time of Chernobyl), these polls have consistently shown levels of support for nuclear power to be higher than levels of opposition.

Other nations have different socio-political and cultural features that influence their publics' attitudes toward nuclear power. For example, France's reliance on nuclear power—a product of energy security concerns after the 1973 oil crisis—had engendered strong support for the technology, although the past two decades have seen that social contract fray. The country initially committed to reducing its reliance on the technology, but more recently, interest has grown in revivifying the French nuclear industry (Chrisafis 2022), driven by concerns regarding energy security and domestic political considerations. Similarly, Japan is restarting some of its dormant nuclear reactors. The salience of energy security as a factor in nuclear power deployment is especially clear in both France and Japan. The German and Italian publics have traditionally been opposed to nuclear power, although the 2022 global energy crisis is forcing Germany to reconsider its planned closure of its few remaining nuclear plants. Belgium decided to phase out nuclear power by 2025, as has Taiwan, although the former recently decided to extend the life of its nuclear plants. South Korea set out plans to phase out nuclear power by 2060, although its new president recently vowed to reverse the phase announced by his predecessor. The long-term stability of this growth in interest is unclear, especially because it seems mostly driven by an urgent but potentially transient global energy crisis. Outside established democracies, the validity of public polling in establishing subjects' attitudes toward nuclear power (and many other subjects) is much reduced. This applies to some autocratic nations that have recently joined the community of nuclear energy states.

Insights from the Social and Decision Sciences

It is difficult to develop a satisfactory taxonomy of the underlying roots of public opposition to nuclear power, but the key factors are certainly known and have been the subject of extensive research over the previous five decades by academics in engineering, psychology, the decision sciences, and the field of science and technology studies. Table 8-1 presents a classification of the roots of public opposition across two dimensions: first, whether the opposition is inherent to nuclear power or applies to other technologies or infrastructure; and second, whether the opposition is more related to the technology itself or the socio-technical institutions that govern it.

Nuclear power is not the only energy technology that contends with societal opposition, and some of the factors in Table 8-1 apply to other infrastructure, including pipelines, transmission lines, and potentially to emergent or unfamiliar energy systems. The implications of addressing the societal acceptance challenge thus extend beyond nuclear energy, making their resolution critical to the deep decarbonization of the global energy system.

TABLE 8-1 A Taxonomy of the Underlying Roots of Public Opposition to Nuclear Power

	Concerns rooted in the individual's relationship with the technology	Concerns with the institutions governing the technology
Inherent to nuclear power	• How would an accident affect my health and safety, as well as that of my family, water, and food? • How would nuclear waste storage affect my health and safety, as well as that of my family, water, and food? • What happens if terrorists attack the plant, either physically or through cyber means? • Will normal operation give me cancer? Would exposure during periods of abnormal operation give me cancer?	• How closely related are the institutions that govern nuclear power to the institutions that govern the nuclear weapons program? • How can I trust the institutions that govern nuclear waste to safeguard it for hundreds of thousands of years? • How can I trust institutions shrouded in secrecy? • How can I trust the numbers generated by these institutions, given the uncertainties in nuclear risk assessment?

Applicable to other infrastructure	• How would this project affect the local community and my sense of place? • Will this project make my life worse by, for example, increasing noise, pollution, groundwater contamination, or ruining aesthetics? • How do this project's risks square with my general attitude to risk—my risk tolerance?	• How are risks being minimized? • What would happen if there were an accident or incident at the facility? • How should I respond to an accident or incident at the facility? • Are the regulatory institutions competent, effective, and powerful? Can they hold operators to account? • Is the community being promised a credible set of benefits? How likely are those benefits to materialize? • Am I, or are we, being consulted in the design and deployment of this technology? Do we exercise a measure of control over it?

NOTE: Concerns regarding this (and other) technologies fall along the dimensions identified by decision scientists who pioneered the psychometric paradigm of risk perception (Fischhoff et al. 1978).
SOURCE: Committee generated from B. Fischhoff, P. Slovic, S. Lichtenstein, et al., 1978, "How Safe Is Safe Enough? A Psychometric Study of Attitudes Towards Technological Risks and Benefits," *Policy Sciences* 9(2):127–152.

Dread and Public Opposition

Social scientists have been exploring the public's perception of nuclear power and the underlying roots of those societal attitudes since the 1970s. A psychometric study undertaken by a group of psychologists in 1978 (Fischhoff et al. 1978) analyzed the attitudes of 76 respondents to a variety of technologies and concluded that "nuclear power had the dubious distinction of scoring at or near the extreme negative end for most of the characteristics [under investigation]. Its risks were seen as involuntary, unknown to those exposed or to science, uncontrollable, unfamiliar, catastrophic, severe (fatal) and dreaded. Medical X rays, in contrast, had a much more benign profile. Nu'lear power's perceived benefits were also assessed and were found to be extremely low" (Slovic 1990, p. 6-3; see Figure 8-2). This general conclusion—that nuclear technology engenders a strong signal response in the public—has been replicated over time and across countries. It was also preceded by a decade-long debate about how the public perceives the risks and benefits of different activities (Starr 1969): this debate helped articulate the importance of risks being *voluntarily* taken for the public to accept them. This was echoed in Roth et al. (1990), which describes the multiple dimensions of risk and the importance of accurate risk comparisons: making risk comparisons between voluntary and involuntary choices can foment mistrust. Furthermore, societal amplification of risk is a well-documented phenomenon (Solvic 1979; Kasperson 2005; Rothman 1987) that is revealed by Figure 8-2, originating from the fear of uncontrollable, involuntary, and potentially life-threatening outcomes.

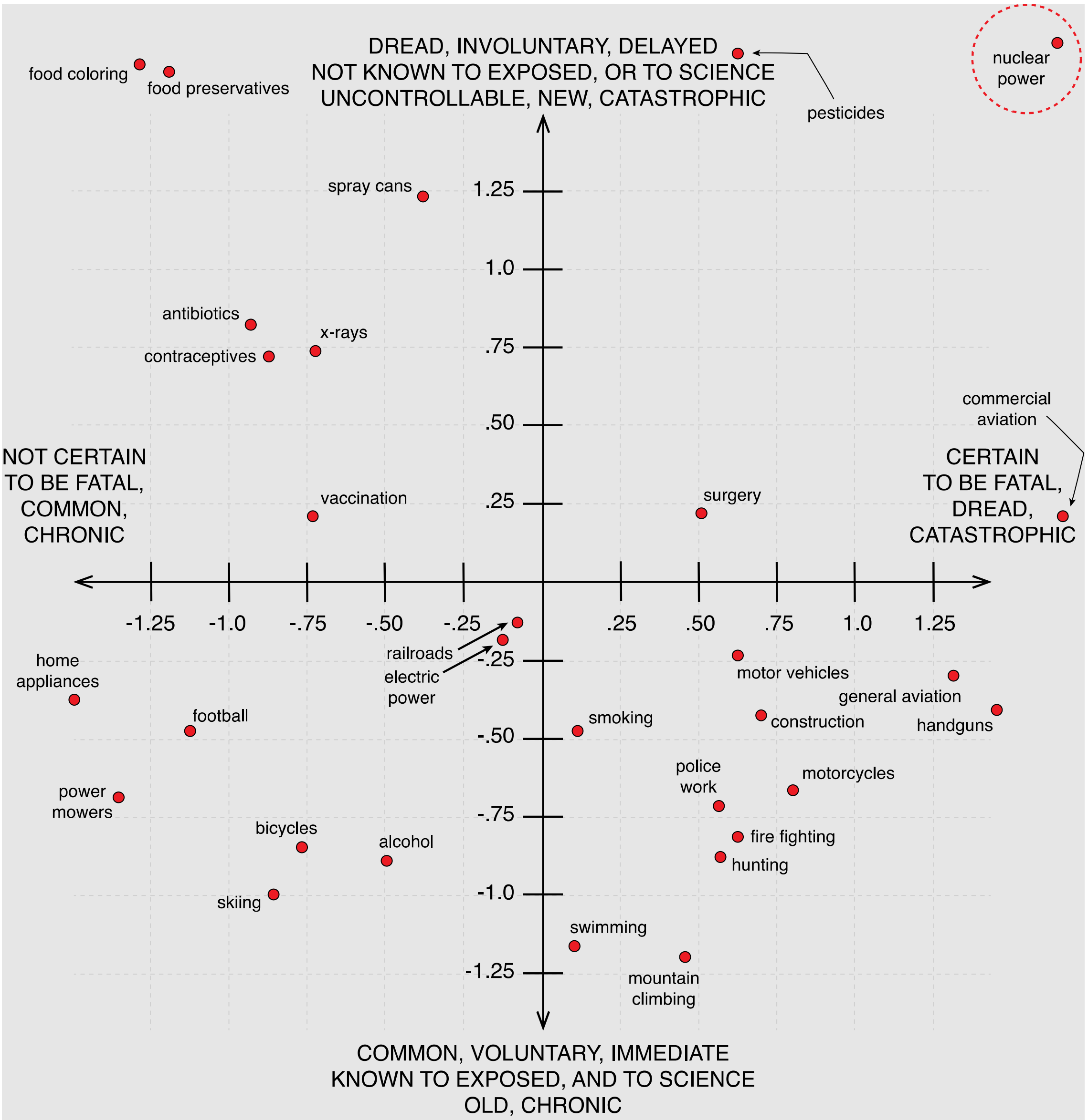

FIGURE 8-2 (A) How safe is safe enough? Results from Fischhoff et al. (1978) show the location of different risks within a two-factor space. The first factor relates to how fatal and catastrophic the risk is perceived to be; the second relates to how voluntary, "known," and controllable it is perceived to be. Uniquely, nuclear power's risk is perceived to be "off the charts" along both scales. (B) These results have been extensively replicated over the past decades.
SOURCE: Committee generated from B. Fischhoff, P. Slovic, S. Lichtenstein, et al., 1978, "How Safe Is Safe Enough? A Psychometric Study of Attitudes Towards Technological Risks and Benefits," *Policy Sciences* 9(2):127–152.

This "dread" partly originates from the fear or radioactivity's attributes and its effects. It is invisible and people cannot control their exposure to it in the event of a nuclear accident. This attribute—controllability—is key to risk acceptance: risks that are assumed voluntarily are more acceptable to people than risks that are thrust on them, which explains why people ski and mountain climb despite the risk of injury and death from those activities being demonstrably higher than the risk of injury or death from a nuclear accident (Starr 1969). Nuclear power is unique among energy technologies in that it is intimately associated with radioactivity, the release of which leads to "dreadful" health impacts like cancer. As a disease, cancer is known to engender dread; James Harrison famously called it "The Dread Disease" (Patterson 1989). This dread risk is equally applicable to non-power facilities like waste repositories, although it is compounded by the specter of long-term (>100,000 year) stewardship, and to dread-inducing events—like terrorist attacks[1]—that could occur at nuclear facilities.

A recent study attempted to disentangle this "dread risk"—the large mix of "gut reactions" or "signals" that come with the nuclear "label"—from nuclear power's catastrophic accident risk. It asked a sample of 1,226 Americans to build an energy mix for the year 2050 that would halve greenhouse gas emissions. Respondents were randomly divided into two subgroups; both subgroups were given information about the technical performance, emissions, and *risk* (in terms of both mortality and morbidity) of six energy sources; half were told the names—or labels—of the six technologies. Those who were "blinded" to the technologies' labels deployed more NPPs as part of the low-carbon electricity generation mix than peers in the other group (on average, ~26 percent of total U.S. electric power generation versus ~19 percent). This study showed the extent to which the label "nuclear," as opposed to its statistical accident risk, limits the deployment of this low-carbon technology (Abdulla et al. 2019).

Some efforts to explain the dread are rooted in demographics. One finding that has been extensively replicated is that women are more opposed to nuclear power than men (Abdulla et al. 2019). People with less expertise in either the nuclear field or in science, technology, engineering, and mathematics (STEM) fields broadly are more likely to oppose nuclear power (Harris et al. 2018). Last, politically left-leaning respondents are more opposed to the technology than their counterparts on the political right. The last result warrants fresh study to see if it still holds, because two recent developments could have instigated a shift in the relationship between political alignment and support for nuclear power. First, there has been a bifurcation among political liberals recently, as industry, some governments, and energy experts promote the view that that nuclear power is essential to deep decarbonization. This strategy has been pursued by successive governments of the United Kingdom since 2000, and the result of that narrative has been what social scientists have termed "reluctant acceptance" among a subset of the population (Bickerstaff et al. 2008). The construction of a narrative that either advocates for nuclear power or frames it as necessary could thus change attitudes to nuclear power. Second, political conservatives have traditionally supported nuclear power precisely because they associate the industry with institutions (e.g., the military) they trust and support: recent developments have led to a precipitous loss of trust in institutions (Leiserowitz et al. 2012; Schank 2022; Pew Research Center 2022), which may or may not reverberate on attitudes toward nuclear power. While there is anecdotal evidence for both shifts, they remain speculative: more research is needed to determine the extent to which they increase of undermine support for nuclear power.

In addition, nuclear power is often seen as dirty: this perception is rooted in its production of harmful wastes (rather tangible and immediately lethal ones, unlike carbon dioxide) (Ansolabehere and Konisky 2014). This perception is especially consequential. More broadly, the public has serious misconceptions regarding different types of pollution: a recent study found evidence that the public does not distinguish long-lived greenhouse gases from short-lived criteria air pollutants (Dryden et al. 2017). In fact, they are quite different. Carbon dioxide lasts much longer in the atmosphere than criteria air pollutants. Consequently, people might not appreciate the risks of greenhouse gases and the importance of deep and urgent cuts in greenhouse gas emissions, believing instead that warming will cease a matter of years after any energy transition. This has large implications on the technologies and policies that the public is willing to support.

Weart identified "nuclear fear" to be prompted by the use of nuclear weapons in World War II and the consequent proliferation of those weapons in the United States and then-Soviet Union (1988). Weapons that could change all life on Earth, as found in the arsenals of the nuclear powers, have produced what sociologist Ulrich Beck has termed a "Risk Society" (1992). Again, this perception has

[1] Terrorism is known to induce the similar type of dread risk.

much to do with radiation's "invisibility" and "controllability": radiation, Beck noted, was particularly insidious because its presence evaded all our senses to detect its potentially destructive force.

In the United States, managers of the nuclear enterprise now stress the value in "distinguishing the sunny side of the atom from its more sinister one" (Ford et al. 2018). The fact of the matter is that the military applications of nuclear technology and the civilian applications have a connection to each other: the two enterprises have a common origin and clearly rely on one another's strengths, most clearly in the connection between civilian suppliers and the naval reactor program, as well as the revolving door that exists between civilian nuclear power and retired Navy personnel. David Lilienthal famously said that research on the two was "virtually an identical process: two sides of the same coin" (Gamson 1987). Social scientists in the UK recently documented the close links between civil and military nuclear industries resulting from pressures to ensure a steady stream of skilled workers in the nuclear weapons and nuclear submarine sector (Stirling and Johnstone 2018). This connection does not engender confidence among those parts of the broader population for whom the association is problematic. An appropriate response from the industry would acknowledge the link while seeking to strengthen the firewall that has been slowly built between the two enterprises. Beyond nuclear power's military associations, any institutions that are secretive are generally viewed with suspicion and are thus subject to mistrust and misconceptions.

The other major challenge that is inherent to nuclear technologies is the demands it makes of our social institutions. Nuclear power requires the long-term stewardship of highly radioactive and long-lived nuclear waste. While safe storage can be accomplished, it requires credible and durable social institutions—a demand of society for "vigilance and a longevity of our social institutions that we are quite unaccustomed to" (Weinberg 1972). A companion study from the National Academies on the merits and viability of advanced reactor fuel cycles and waste (NASEM 2022a) has pointed out that the fact that the United States has failed to resolve the problem of nuclear waste forty years after the passage of the Nuclear Waste Policy Act, has further compounded the issue of lack of trust in institutions.

> Finding 8-2: There exists significant tension between the secrecy and security required by the institutions that develop, deploy, and regulate nuclear power—and the transparency and openness that are hallmarks of best siting practices and community support. This is inevitable, but resolving or managing the tension would support efforts to expand nuclear power, especially if plans for widespread national or international deployment are envisioned.

The Problem of Trust

Much research has been devoted to the role of trust in the persons and institutions who are responsible for the promotion and management of nuclear energy. This strand of academic research emphasizes the public's lack of trust in the nuclear industry's "risk communicators"—the scientists, engineers, regulators, and policy makers who aggressively support the technology.

The nuclear industry and its promoters make claims of safety, including instances from reactor accidents. For example, on the tenth anniversary of the Fukushima accident, one commentator claimed that, "Amid all the tsunami and evacuation deaths, the reactor itself proved to be close to harmless" (Saunders 2021). Another said, "[T]he radiation from Fukushima and Three Mile Island will kill zero people. In other words, the main lesson that should be drawn from the worst nuclear accidents is that nuclear energy has always been inherently safe" (Shellenberger 2019). Studies have broadly acknowledged that there are few (if any) deaths expected from radiation exposure in the case of the Fukushima nuclear disaster, but it is debatable whether this argument changes enough minds for nuclear power to witness radically expanded deployment. In fact, the Fukushima accident is widely and correctly seen as a disaster in many dimensions, including its impact on public trust in the institutions involved in advancing nuclear power.

Often, claims of public misunderstanding of nuclear power and radiation are made along with the assertion that if only the public had the proper scientific education—the right facts—they would not fear radiation and understand the benefits of nuclear power (Weart 1988). This lack of understanding as the source of the trouble is what has been termed the "deficit model of public understanding of science" (Wynne 1991). Most studies support at best only a small positive relationship between scientific knowledge and perception. Confidence in science varies based on age, race, educational attainment, region, political ideology, and other characteristics (AAAS 2020). As a result, social scientists now focus on other factors that play a larger role in shaping public attitudes (AAAS 2018).

Wynne pointed out that people judge whether scientific knowledge is trustworthy and therefore useful by comparing it to what they already know to be true based on their own experience. For instance, predicted incidences of cancer will be judged against known cancer incidences near facilities in question, even if those cancers were not caused by those facilities. Context is also important. Wynne gives an example of Sellafield workers who were ignorant of radioactive processes and didn't feel that they needed to know about them because important safety information was incorporated into the ways in which they were trained and approached their work. In other words, the workers needed only to learn the procedures, not the science behind them. The important lesson is

> That public uptake (or not) of science is not based on **intellectual capability** as much as social-institutional factors having to do with social access, trust, and negotiation as opposed to imposed authority. When these motivational factors are [in] position, people show a remarkable capability to assimilate and use science or other knowledge derived (inter alia) from science. (Wynne 1992; emphasis in original).

Studies suggest that nuclear power is one of the safest means of power generation (Markandya 2007), but this does not mean that people will favor it. In the past decade, emerging research suggests that increasing levels of scientific literacy and numeracy are not correlated with increased acceptance of the dominant scientific and engineering consensus. Instead, more education enables people to selectively employ scientific information in support of their preconceived notions—notions already rooted in instincts, feelings, identities, or outlooks (Kahan et al. 2012). Indeed, recent research shows that underlying factors, such as group identity, can strongly influence people's attitudes and acceptance of scientific information. That is, the foundational beliefs of a group can strongly influence its members' willingness to accept and act on scientific evidence. The problem is more complicated than the deficit model acknowledges, and significant research is necessary to understand how cultural experience and group identity shape trust in scientific information (AAAS 2018, 2020). The bottom line is that more education is not likely to be an effective response to those who harbor misgivings of nuclear technology.

Claims of nuclear safety, as many social and decision scientists have highlighted over the past decades, often fail to convince a reticent public. Trust is essential to public acceptance and support of nuclear power. Without establishing public acceptance, any future deployment of nuclear power at a level that matters for climate change mitigation is destined to fail. The notion suggested by Alvin Weinberg 55 years ago, by John Kemeny 40 years ago; and by Paul Slovic stated 30 years ago, still holds:

> Before we spend billions of dollars pursuing a path that is destined to lead to failure, we should pause for a moment to confront the problem of trust. Restoration and preservation of trust in risk management needs to be given top priority. A solution to the problem of trust is not immediately apparent.… The problem is not due to public ignorance or irrationality, but is deeply rooted in individual psychology and in the adversarial nature of our social, institutional, legal, and political systems of risk management … without a serious effort to address the problem of trust, neither public acceptance nor a rebirth of civilian nuclear power in the United States will be achieved. (Slovic 1990)

Opposition Rooted in Factors That Are Common Across Technologies

Some of the factors that lead to opposition are not specific to nuclear power but are common across energy (and some non-energy) technologies. At the level of the individual, the notion of "proximity" or "place" figures prominently in social scientific research on public acceptance of energy technologies, including nuclear power (Venebales 2012). The deployment of energy infrastructure, especially if it is large and strikingly visible, alters an individual's relationship with the land—be it wind farms, transmission lines, NPPs, or carbon capture facilities. The concern is twofold. First, the disruption that is caused during construction—noise pollution, light pollution, air pollution, water pollution (this concern is salient in rural areas that rely on groundwater wells), and construction traffic. If developers and workers are perceived to be outsiders, the concern is magnified. Second, and once the construction phase is complete, there is the more permanent alteration of land, nature, or potentially community dynamics. These concerns manifest themselves at the level of both the individual and the community.

An additional factor is opposition that is rooted in distrust of the industry's technical experts. To some extent, this is common across complex or sensitive technologies. One reason is the (correct) understanding among publics—be it implicit or explicit—that the generation of science and the dynamics of power and culture are inextricably linked; Jasanoff (2004) describes how scientific knowledge and the social order are "co-produced." This affects trust in science, especially among the powerless (see Box 8-2 for a note on environmental justice). Another reason is the perceived arrogance of some experts—engineers, executives, and their allies. Trust is especially undermined if experts dismiss public concerns, or when these concerns are perceived to be dismissed by a community engagement process that has been established to extract them. This is especially unfortunate: the field of risk assessment has known for decades about Normal Accidents[2] (Perrow 1999), the limitations of scenario analysis, and the cognitive limits of expert judgment. Social science has since evaluated this phenomenon in particular: Beck noted that "our risk assessment bureaucracies have found ways to deny systemic hazards" (Beck 1999) and Downer has written extensively about how complex risks are not "objectively calculable" (Downer 2013). The attitude reveals a cultural challenge that may be acute within the nuclear industry, but one that is not unique to it: all industries have analysts and employees who take an optimistic view of the benefits of their technology (and place an undue amount of confidence in its prospects). Motivated reasoning also exists among opponents of nuclear power.

The nuclear industry's institutional practices have advanced greatly since Three Mile Island, and the formation of the Institute for Nuclear Power Operations (INPO)[3] in the United States is rightfully lauded as one of the industry's greatest successes. However, in community engagement sessions, the notion persists that most problems not only warrant but also have a technical solution. While technical solutions exist to many socio-technical problems, not all problems can be resolved with technical modifications. It would be prudent to ensure that these views change and not emerge during public engagement sessions, because such pronouncements end up undermining trust in nuclear energy projects and in the broader industry.

The factors described above mold societal preferences toward different energy technologies; some of them could be difficult to alter once established. They are the by-product of deeply engrained instincts, outlooks, feelings, or judgments. However, public acceptance or opposition is not *entirely* rooted in psychology and behavioral science. At one level, acceptance of new energy infrastructure hinges on the relevant stakeholders' assessments of its benefits, costs, and risks. If a community's calculus yields an assessment that nuclear power's benefits exceed its costs, the community might become supportive of hosting a reactor. To achieve these beneficial assessments, developers need to consider two facts. First, evidence from the social sciences suggests that the benefits of nuclear power are undervalued: its electricity is not perceived to be "clean" (Ansolabehere and Konisky 2014), since it produces long-lived

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[2] The premise that a combination of human error and systemic failures across a multitude of systems can cause accidents to escalate, and that such accidents are inevitable in extremely complex systems.

[3] INPO sets industry-wide guidelines for NPP operations. It is funded by the nuclear industry.

waste; its true benefits are either very concentrated (salaries paid to plant workers) or very diffuse (electricity that feeds into the bulk power grid, for which people know there are alternatives, some of which might be more acceptable). The second difficulty is that different individuals and communities attribute differing weights or values to different decision criteria.

BOX 8-2
Environmental Justice and Nuclear Power

Another challenge that affects communities' assessment of nuclear power's risks and benefits is the lack of attention that has historically been paid to issues of environmental justice. Class, race, and power affect the distribution of the environmental burdens that are generated by all industries, including resource extraction and energy generation. Differential economic power across classes and races often explains proximity to hazardous sites; it is also apparent in the distribution of pollutant releases and the ability of the affected communities to move out of harm's way. Of course, injustice manifests not just in economic form; it can be regarded as "also a culture, juridical, and psychological phenomenon" (Mohai et al. 2009). This is perhaps especially true in the case of Indigenous communities that have very strong ties to their native lands and where systems of injustice have been entrenched over centuries.

In the United States, political action on environmental justice was borne out of the civil rights movement and has since led to the integration of environmental justice appraisals in federal bodies. The body of academic literature on environmental justice is also growing rapidly and has focused on "three main dimensions: *distribution, procedure,* and *recognition*" (Cotton 2021). *Distributive environmental injustice* can be especially prominent in nuclear projects: the costs of NPPs are often incurred, at least partially, by taxpayers and local communities (during construction). The benefits, meanwhile, accrue to a broader population and established interests like financiers and industry. Should a nuclear accident occur during fuel transportation or operation, the local community incurs the greatest cost, making the risk "intensely geographical." *Procedural justice* is also necessary to site the next generation of nuclear reactors and is the topic of the next section of this chapter: multiple meaningful avenues need to exist for public participation in the decision-making process—be it during design and siting or decommissioning. Last, *recognition justice* must be sought: past and present concerns among Indigenous and other communities should be acknowledged while decisions are being made.

Cotton suggests four elements for evaluating whether nuclear power policy and planning processes are acceptable. First, "the onus on justifying the impositions of environmental burdens on … affected communities rests with the … developer." Second, "unequal treatment must be compensated for" through wealth redistribution or other benefits. Third, stakeholders "must have access to unbiased and complete information about environmental impacts and harms." Fourth and last, affected communities must be included "through fair participatory processes" and must give "free, informed, and autonomous consent to environmental change given all the aforementioned criteria" (Cotton 2021).

These suggestions correspond with the wealth of experience from previous successful and failed community engagement efforts, as the best practices section below will show.

Nonetheless, the characteristics and aspirational goals of new and advanced nuclear reactors—like reduced capital cost, smaller plant sites and emergency planning zones, and smaller radionuclide inventories—might alter people's assessment of the benefits, costs, and risks, and make some willing to host reactors in their communities. For example, solving the economic challenge—which figures prominently in community engagement sessions, although behind safety and waste—can increase societal acceptance. Just like poor societal acceptance could incur costs to a project developer, demonstrating affordability and economic competitiveness while still achieving high levels of safety and reliability could increase societal acceptance: it is a two-way street. This is true across energy and non-energy infrastructure, especially for megaprojects which often end up over budget and behind schedule—the sheer size of the investment, the poor cost and schedule control that often exists, and the broader effects on the local community attract special scrutiny and reduce societal acceptance.

Many of these concerns manifest themselves at the level of both the individual and the community. Moreover, much of the social scientific research underpinning this section hinges on the crucial fact that there are multiple publics: a developer that focuses on the wrong publics when conceptualizing and executing a project—that is, when shaping the project's context and articulating its benefits and costs to those affected by it—boosts the likelihood of project failure. For example, there is a difference between the broader public, the topic of this chapter's discussion thus far, and local publics. Acceptance of nuclear power is higher among people who are proximate to some nuclear plants. Clearly, it is important to distinguish between the broader public and various local publics that extract rent or other, more diffuse benefits from NPPs.

CHARTING A PATH FORWARD: BEST PRACTICES FOR COMMUNITY ENGAGEMENT

Avoiding Risk Communication Strategies That Have Failed in the Past

Future success in siting NPPs requires, first and foremost, avoiding strategies that have failed to assuage public concerns in the past. Broadly, strategies to be avoided can be divided into two clusters.

The first collectively appeal to what has been termed the "engineer's myth"—that, "for any problem associated with any technology, there are technical modifications that would alter the risk calculation and fundamentally change public attitudes to its deployment" (Abdulla et al. 2019). This problem is not limited to the nuclear industry but stretches across many industries.

Two manifestations of the engineer's myth are currently active. Developers promise that their new designs will greatly reduce core damage frequencies or successfully prevent the most salient accident scenarios imaginable. More recently, the focus has shifted away from specific accident pathways and toward pathway-agnostic paradigms, the most prominent of which is the claim of a "walkaway safe" or "foolproof" reactor. This attitude is laudable, but the industry must be reminded that, thanks partly to the efforts of its engineers, existing reactors are quite safe. The point is that this argument often fails to convince reticent members of the public, and there is no evidence that new terminology will change that reality.

More importantly, foregoing this strategy would serve the industry much better: if an accident occurs in a "walkaway safe" reactor, that could undermine trust in the enterprise in an acute way from which it would be difficult to recover. Even where it exists, societal acceptance is often fragile, and events could quickly change public perceptions. Moreover, new, more severe accident pathways can always be envisioned (Downer 2013), so the claim is *prima facie* inappropriate. Last, as discussed in Chapter 7, some advanced reactors raise new issues to be analyzed for safety, despite minimizing the risks from more familiar vulnerabilities of LWRs. In the end, the claim is *unnecessary* when engineers are designing reactors to exacting levels of safety.

The other manifestation of the engineer's myth is the focus on automation as a convincing answer to nuclear accidents. Human error has indeed been responsible for causing substantial harm in this and other domains, and automation could potentially prevent errors or yield efficiencies. But it must be recognized that automation introduces its own risks—new pathways by which accidents can arise, some of which have yet to fully understood and eliminated. Thus, automation can be part of the answer to the question of human error, but only if it is subject to careful, dispassionate analysis to assess and eliminate vulnerabilities. However, automation must be weighed alongside the expectations of jobs and economic growth for a community; a more detailed discussion of employment impacts can be found in Chapter 6.

The second cluster of strategies that the industry must avoid is rooted in the deficit model of science communication: the reason for poor societal acceptance of nuclear power is *not* a lack of understanding or a lack of information. Decades of research in the social sciences have established this fact. Like many other risk communication strategies, lamentations about the poor scientific literacy and numeracy of the general population are not unique to the nuclear industry.

At its most benign, the deficit-model strategy can be insensitive (described above in *the problem of trust*). At its least benign, it can be hostile to publics with valid concerns about nuclear power, and it undermines trust in the enterprise. Over the decades, some executives and engineers witnessed this strategy's ineffectiveness and became especially wary of engaging with the public. Caution in engaging with potentially hostile stakeholder is understandable, but it would also mean learning the wrong lesson from the failure of this risk communication strategy. The problem is not in the engagement, but rather in the content of the communication and the attitude of the communicator. To the extent that this communication strategy persists within the industry—be it habitual or ingrained—solving it would be extremely beneficial to the enterprise.

Finding 8-3: Risk communication strategies that rely exclusively or greatly on the engineer's myth and the deficit model of science communication have been tried in the nuclear industry and have failed comprehensively.

Recommendation 8-2: To improve the prospects for nuclear deployment in coming decades, nuclear vendors need to employ new risk communication strategies, including those grounded in rigorous social science (rather than polling) and respect for community apprehensions and desires. Moreover, risk communication strategies need to remain robust and endure for the life of a nuclear plant, not just during construction. Different methods and frameworks for engagement may be required in each phase of a plant's lifetime.

The reliance on these strategies is partly the result of an engineering education that does not sufficiently emphasize the social consequences of technology use. Although all accredited engineering programs are required to emphasized ethics, efforts must be initiated to highlight the social impacts of technology design and deployment, especially as the theories and methods for doing so have developed greatly. The result will be an engineering workforce that has deep technical training while being considerate of socio-technical issues, undertaking sophisticated analyses at the interface of engineering and social science.

Finding 8-4: Academic training in nuclear engineering, and in many engineering fields broadly, has focused on deep technical training without sufficient considerations of the social consequences of engineering decisions.

Recommendation 8-3: U.S. academic institutions need to take the lead in promoting socially conscious engineering. Within the nuclear energy field, the Nuclear Engineering Department Heads Organization and the American Nuclear Society Education, Training, and Workforce Development Division should engage with experts in the social sciences of design and siting to collaborate, develop, and implement a set of recommendations for updating curriculum, accreditation, scholarship and fellowship programs, as well as research programs. This includes economics, ethics, social science, and the importance of historical decisions and practices that left negative impressions of nuclear technology. While integrated engineering teams should include a broad range of experts crossing many disciplines, engineers, who often lead design teams, should be trained to appreciate the social components of design choices.

Acknowledging Factors That Might Affect Societal Acceptance of Nuclear Power

Some preferences, like habits, can be difficult to change once they are deeply instilled in individuals or communities. However, public attitudes to technologies—no matter how difficult—*can* change. In the case of nuclear power, four factors could affect societal acceptance of the technology over the coming years and warrant special mention.

The first of these is the threat of catastrophic climate change. As individuals internalize the scope of disruption that is occurring now and begin to grapple with the likely scale of disruption in the near future, society will change. In a sense, the bifurcation in public attitudes toward nuclear power that has occurred among environmentalists (who are now more likely to favor nuclear) could extend throughout the population. The "benefits" of nuclear power might become more convincing to some publics in a world that is contending with perpetual climate emergency.

The second is the growing lack of trust in institutions and the declining cohesion of societies. This could make orchestrating a radical expansion of nuclear power difficult or more contentious, especially since building and operating NPPs safely and securely is highly dependent on institutional quality, to say nothing of the social institutions required for long-term stewardship of nuclear waste. Both these arguments are speculative, but major evolutions in societal acceptance are possible.

The third is energy security: several countries turned to nuclear power historically because of these concerns, with France and Japan being the two most prominent examples. The argument that nuclear can enhance energy security often reemerges when fossil energy prices rise, or geopolitical tensions threaten energy supplies: one example is Belgium's decision to continue operating some of its nuclear reactors past their planned phaseout date as a result of the 2022 economic crisis and the Russian invasion of Ukraine.[4]

The fourth and final factor comprises unpredictable disruptions in the policy space. One example of such a disruption is the German Government's decision to accelerate the closure of some nuclear plants after the Fukushima disaster. It is very plausible that similar unpredictable disruptions might occur in the future and yield equally consequential (or more consequential) policy shifts. While many plausible disruptions would enhance the prospects of nuclear power, readers must be reminded that some could diminish its prospects. Therefore, it is essential not only to avoid risk communication mistakes of the past, but also to adopt a set of best practices for community engagement, summarized below.

Recent U.S. Efforts to Incorporate Consent-Based Siting in Decision Making

Public discussions about consent-based siting of nuclear facilities in the United States have typically centered on the disposition of spent fuel from commercial reactors. While the 2012 Blue Ribbon Commission on America's Nuclear Future noted the value of using consent-base processes in siting a used fuel repository, the United States has not actively pursued a consent-based siting process. The Nuclear Waste Policy Act of 1982 and subsequent amendments do not allow for any site other than Yucca Mountain in Nevada to be actively pursued without explicit Congressional approval (EPA 2013). The U.S. Nuclear Regulatory Commission (NRC) has received two applications to build and host a consolidated interim spent fuel facility, in New Mexico and Texas (NRC 2020). But both are confronting political opposition in these states and their future prospects are uncertain—there are often no guarantees with siting (see Box 8-3).

Limited efforts have been initiated to outline a consent-based process that might be used if the Nuclear Waste Policy Act were changed. In 2017, the Department of Energy (DOE) released a "Draft Consent Based Siting Process for Consolidated Storage and Disposal Facilities for Spent Nuclear Fuel and High-Level Radioactive Waste." This was followed almost 5 years later by a December 2021 "Request for Information on Using a Consent-Based Siting Process to Identify Federal Interim Storage Facilities" (DOE 2021). The 2021 Request for Information asked for inputs on consent-based siting processes, removing barriers to participation, and interim storage's role as part of a waste management system. DOE indicated that "responses to the RFI will inform development of a consent-based siting process, overall strategy for an integrated waste management system, and possibly a funding

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[4] The decision to extend reactor lifetimes has generated consternation among the owners. Engie has requested federal government support to finance the extension in the fear that the 2022 energy price spike will be short-lived, and that any extension will ultimately prove unprofitable (Carter 2022).

opportunity." As of February 2023, DOE announced $26 million in available funding for these activities (DOE 2023).

The NRC requires applicants for a siting license to address environmental justice—specifically impacts on minority and low-income populations and ways to mitigate these impacts—in their standard review plans as part of their efforts to comply with the National Environmental Policy Act (NEPA), but community engagement is limited. In 1999, the NRC updated its standard review plans for environmental reviews for NPPs (NUREG-1555). The reason for the update was, at least partly, to issue fresh guidance regarding the impacts of facilities on socioeconomic issues related to demography, community characteristics, historic properties, and environmental justice (NRC 1999). The standard review is typically performed once a design is complete and a site has been identified as a preferred location for a new reactor, rather than as a consent-based approach. In 2021, the NRC did open a public comment period to "assess whether environmental justice is appropriately considered and addressed in the agency's programs, policies, and activities" (NRC 2021).

Discussions regarding consent-base processes in the design, siting, and deployment of advanced reactors are nascent. In 2015, the Electric Power Research Institute (EPRI) updated its "Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Power Generation Facilities (Siting Guide)" (EPRI 2015) This siting guide describes a multi-step site selection process that sequentially reduces the area of consideration for a proposed facility, starting with a "region of interest" and ending with the "ultimate identification of a proposed and alternative sites." The guide does encourage an analysis of socioeconomic factors specified by the NRC and discussed above.

In early 2022, the National Reactor Innovation Center (NRIC) introduced a new tool called the Siting Tool for Advanced Nuclear Development (STAND), created in partnership with Argonne National Laboratory, Oak Ridge National Laboratory, Idaho National Laboratory, and the University of Michigan's Fastest Path to Zero Initiative. STAND is described as a user-friendly decision tool that supports current and emerging advanced nuclear companies in locating potential host communities. STAND's expansive data sets go beyond traditional proximity and safety siting data to also include socioeconomic data at the community level, which will help facilitate the siting process. The tool is not intended to replace community engagement, and its utility will be determined as users exercise its capabilities.

These efforts are an excellent start and could make a difference if they are undertaken in good faith and with deep commitment. However, there is a large literature on value-focused thinking and designing engineering technologies to reflect community values (Keeney 1996; Dignum 2016; van de Pol 2022): the industry does not approach reactor design in this manner, even though these approaches have been demonstrated to lead to more creative decision-making. The transition to value-focused thinking is urgent. Organizations interested in boosting the likelihood of nuclear deployment to aid the low-carbon transition must therefore encourage creative, multi-disciplinary decision-making when it comes to both designing and siting.

> Finding 8-5: Empirical evidence (in the form of new conceptual reactor designs proposed over the past two decades) suggests that public engagement during design and designing for values remains far removed from how nuclear reactor designers approach their tasks; this is especially true for engineers who are trained to focus on technical issues.
>
> **Recommendation 8-4: The advanced nuclear industry, guided by experts who understand the effect of social interactions on design choices, should devote resources to public engagement during the front-end design phase to ensure that products are best aligned with values. This might minimize the opposition to the licensing process for any specific site. To maximize the probability that a specific design is acceptable to the largest number of communities, reactor designers must engage with potential host sites well in advance of submitting their design certification documents to the regulator: only then could they realistically address public concerns and mitigate them in their proposed plans. This does**

not mean that each site needs a different design, but that community concerns broadly are considered while designing a nuclear energy system.

Best Practices in Community Engagement

The findings and recommendations in this section are derived from peer-reviewed research that has been published by experts in the social and decisions sciences, and from a workshop organized by the committee in September 2021 which brought together some of these experts to discuss the subject (NASEM 2022).

Are there models of how to engage successfully on difficult issues such as siting nuclear power facilities? The answer is yes. In fact, the siting of nuclear waste facilities offers transferable lessons for the nuclear energy industry. For example, in the two communities that vied to host Sweden's high-level nuclear waste repository, more than 80 percent of the public supported the facilities (SWI 2022). Based on historical experience of nuclear waste repository siting, in no democracy has a "decide-announce-defend" method of site selection worked. The only democracy attempting to rely on that method, the United States, has not been able to complete the process 35 years after Congress selected the Yucca Mountain site as the only one to be examined and 20 years after Congress and the President approved the site (see Box 8-1 above).

Using the experiences of the United States, Canada, Sweden, Finland, Switzerland, France, and others, researchers have been able to identify some elements necessary to a successful siting process (e.g., BRC Report 2012; Reset Report 2018). These include *having a participatory process* of site selection that includes significant public participation and listening on the part of the implementer. It is important to note that the participatory process will involve iterative engagement over a period of years, perhaps even decades.

Also necessary is a *right to veto or opt out* for an affected community. Most programs limit the opt-out right at some point in the process (at the point of license application, or when a license is granted). Which jurisdictions can have a say (city, county, state, as well as Native American nations) and the form of that decision-making, by referendum, decision by elected officials, or some other method will be important to clarify ahead of time. *Some form of compensation* is granted for affected communities either by way of monetary payment or by in-kind compensation. In Sweden, for instance, to keep both potential host communities under consideration while technical studies were being completed, the selected community would receive 25 percent of the monetary compensation whereas the "rejected" community would receive 75 percent. The idea was that the selected community would benefit in perpetuity from jobs and additional business from the waste facility compared with the "rejected" community (Blue Ribbon Commission 2012). In Finland, the affected community was provided the benefits of increased property tax on the waste facility (Kari et al. 2021). The Energy Communities Alliance (ECA), a public interest group that works with communities adjacent or impacted by DOE activities, has published a guidebook for working with local governments (ECA 2014).

Successful repository siting projects also include funding for the affected communities to *conduct independent technical analyses* of the site so that they do not have to rely solely on the implementer for their information. This ability can increase trust of the implementer and reassure the community. Some siting programs such as that in Sweden have included *funds for public interest groups* that might oppose the siting project. The thinking is that a good opponent will point out potential flaws and improve the overall site evaluation. *Legal partnerships* between the implementer and the local community have also proved successful, but this implies that the local community, through the partnership mechanism, has a voice in the planning and implementation of the project (NEA 2009; Bergmans et al. 2015).

The ability to partner or *retain some control* over a facility can be important in the successful siting and operation of a repository. The Blue Ribbon Commission (2012) found that at the Waste Isolation Pilot Project in southeastern New Mexico, the ability of the state to retain some oversight of the facility through the Resource Conservation and Recovery Act (RCRA) was essential in gaining its support. Some of the waste disposed of in WIPP was expected to be mixed waste, including a hazardous waste component, which would fall under the purview of RCRA. (The Environmental Protection Agency had delegated its authority to some states.) As a result, the state of New Mexico retained the ability to shut down the WIPP facility if it deemed it in violation of safety standards under RCRA.

Beyond a few key practices outlined above, there is no one-size-fits-all design for community engagement processes. In fact, *nuclear power plants may require multiple community engagement process designs*, one optimized for the siting and plant configuration phase, another for regular operation, and yet another tailored to decommissioning and waste removal. Their characteristics are highly dependent on the local context, including geographic location, existing natural hazards and other risk profiles, form of government, and other characteristics.

BOX 8-3
No Guarantees with Siting: The Case of the Deep Geologic Repository at Bruce

Ontario Power Generation (OPG)—the company responsible for operating Ontario's fleet of eighteen pressurized heavy water reactors—was hoping to construct a Deep Geologic Repository (DGR) for low and intermediate-level wastes at the site of its Bruce Nuclear Generating Station. Although the DGR project had been submitted to regulators in 2005, the company made the momentous decision in 2013 to only construct the DGR if residents of the nearby Saugeen Ojibway Nation (SON) supported it. In January 2020, the members of SON voted no on the proposal. OPG respected the vote and began exploring alternative solutions for managing the waste generated by its NPPs at Bruce, Pickering, and Darlington.

While the outcome for OPG was unfortunate in this case, the company did three things that provide a lesson to companies interested in siting energy infrastructure. Specifically, companies should provide a "triple lock" commitment to (1) engage in respectful dialogue with local host communities; (2) not proceed without the support of the community; and (3) respect the decisions that are ultimately made by the community.

Last, *trust in the implementer as well as the regulator* are essential in moving forward. If the implementer, in this case nuclear plant operators, nuclear reactor vendors and manufacturers, and nuclear construction companies, as well as the NRC are not trusted, a plant will not go forward.

When it comes to trust, there must first be an *overriding commitment to honesty*. Exaggeration should be avoided. Candor is the essential foundation for establishing trust. Transparency—the sharing of information and knowledge—is essential to success as is openness, the willingness to listen and to be willing to make meaningful adjustments or changes based on what you have heard. Organizations looking to site NPPs must be prepared to spend significant time and money to ensure success. Siting of these facilities is not the last box to be ticked on a list. This is a social process that takes time to build relationships necessary to gain trust.

Second is the issue of *timing*. Developers must begin working with the community early—not present their plans as a fait accompli. Developers must also understand the local government structure, local public interest groups, and any significant concerns of the public. Moreover, natural supporters must not be treated preferentially. Those institutions should either be engaged with at the same level as natural opponents or, preferably, held at arm's length while the community deliberates on the proposal.

Third is the question of *communication strategy*. Experts in public engagement exist: they should staff the community engagement process if engineers or executives do not have the requisite experience. Experienced staff include properly trained facilitators, mediators, or negotiators, as well as experts who know how to develop an understanding of the relevant actors and concerns in a given community. Relying on existing staff to take on these roles is a recipe for failure. Community engagement is not "the easy part" of the project. It is the most difficult and among the most important, and it must be engaged in sincerely and with due humility.

Multiple, *credible communication channels* must be developed and deployed between developer and community. These include channels to acquire information or data; channels to raise concerns regarding the project or its impact on the community; and channels to share time-sensitive information in cases where doing so is necessary (e.g., if there is an incident at the plant). Although multiple levels of government are likely to be involved in emergency response, the community must be empowered to hear of such developments from the developer itself—this contributes to trust, mutual respect, and the sense of partnership and control that communities need to feel and exercise.

Consistency is important. When presenting facts and figures, the developer's vision for the project cannot change as the political (or social) winds change. Facts and figures must represent the developer's best working knowledge of the issue at hand. Moreover, the developer's treatment of different stakeholders cannot change midstream, especially if they raise concerns about the project. This undermines trust in the entire project and increases the likelihood of failure.

Successful community *engagement is an iterative process*, much like extended diplomatic negotiations. The developer must be prepared to invest the time and effort that is required to listen and act on the community's concerns. Moreover, the communities must be given an opportunity to opt out at some point in the process, as well as a sense of control over the facility. This engenders trust and faith in both the developers and the process. This sense of control can take a variety of forms. Perhaps accessible, real-time radiation monitoring is adequate (as is done in South Korea at NPPs), or the ability for occasional full-body radiation scans (as is done at the Waste Isolation Pilot Project in southern New Mexico). As it works to move its waste to an Independent Spent Fuel Storage Installation (ISFSI), the San Onofre Nuclear Generating Station organizes occasional visits to the plant site for both nuclear opponents and members of the community.

Some projects have been successful through the *formation of partnerships* where the community has a real say in the design and implementation of the facility. This requires the implementer to cede a degree of power over the project (Bergmans 2008; Bergmans et al. 2015).

Most communities *cannot be bought off*. Some will require compensation in addition to the prospect of jobs; others will not. Developers keen on boosting the likelihood of success should provide funding to communities so that they can hire their own independent experts to understand the risks and benefits. This process will engender trust and reassure the community of the safety of the project. Enlightened developers should be prepared to provide some funding to opposition groups who will work to make the project stronger and better. They are a natural "red team"; supporting and addressing their critiques will further increase trust.

Last, *be prepared to walk away* if, after a concerted effort, the community decides that they are not going to willingly host of a nuclear power facility (see Box 8-3). There are no guarantees with siting.

While following the recommendations in this chapter could potentially increase the cost and schedule of a new project, ignoring them could lead to more significant cost and schedule issues. Thus, a preventative strategy may be the best strategy for nuclear vendors—following best practices for community engagement will ultimately result in payoff in the later stages of deployment.

Finding 8-6: The advanced reactor community in the United States is still in its nascency, and therefore has no experience in dealing with potentially challenging siting issues associated with (1) constructing a variety of new nuclear reactor designs at many new locations inexperienced with nuclear power and (2) deploying a variety of novel operational paradigms that are different from nuclear power's traditional role as a baseload electric power generator.

Recommendation 8-5: The developers and future owners that represent the advanced nuclear industry should adopt a consent-based approach to siting new facilities. The siting approach will have to be adjusted for a particular place, time, and culture. The nuclear industry should follow the best practices, including (1) a participatory process of site selection; (2) the right for communities to veto or opt out (within agreed-upon limits); (3) some form of compensation granted for affected communities; (4) partial funding for

affected communities to conduct independent technical analyses; (5) efforts to develop a partnership to pursue the project between the implementer and local community; and (6) an overriding commitment to honesty. Following these practices will require additional time and financial resources to be allotted to successfully site and construct new nuclear power facilities, and the industry should account for these costs in their plans. The industry should be willing to fully engage with a community, hear its concerns and needs, and be ready to address them, including adjusting plans. While this would raise the likelihood of successful deployment, it is not a guarantee of success. Additionally, the industry, guided by experts in consent-based processes, should capture best siting practices in guidance documents or standards.

REFERENCES

AAAS (American Academy of Arts and Sciences). 2018. *Perceptions of Science in America*. Public Face of Science Initiative. Cambridge, MA: American Academy of Arts and Sciences.

AAAS. 2020. *The Public Face of Science in America: Priorities for the Future*. Public Face of Science Initiative. Cambridge, MA: American Academy of Arts and Sciences.

Abdulla, A. 2015. Preserving the Nuclear Option: Overcoming the Institutional Challenges Facing Small Modular Reactors. An Opinion Piece for the International Risk Governance Council. Lausanne, Switzerland: IRGC.

Abdulla, A., P. Vaishnav, B. Sergi, and D.G. Victor. 2019. "Limits to Deployment of Nuclear Power for Decarbonization: Insights from Public Opinion." *Energy Policy* 129(June):1339–1346. https://doi.org/10.1016/j.enpol.2019.03.039.

ANS Task Force (American Nuclear Society Task Force on Public Investment in Nuclear Research and Development). 2021. "*The U.S. Nuclear R&D Imperative*." American Nuclear Society Task Force on Public Investment in Nuclear Research and Development. La Granee Park, IL: American Nuclear Society.

Ansolabehere, S., and D.M. Konisky. 2016. *Cheap and Clean: How Americans Think About Energy in the Age of Global Warming*. First MIT Press paperback edition. Cambridge, MA: MIT Press.

Beck, U. 1992. *Risk Society: Towards a New Modernity*. Theory, Culture and Society. Newbury Park, CA: Sage Publications.

Beck, U. 1999. *World Risk Society*. Malden, MA: Polity Press.

Bergmans, A. 2008. "Meaningful Communication Among Experts and Affected Citizens on Risk: Challenge or Impossibility?" *Journal of Risk Research* 11(1–2):175–193. https://doi.org/10.1080/13669870701797301.

Bergmans, A., G. Sundqvist, D. Kos, and P. Simmons. 2015. "The Participatory Turn in Radioactive Waste Management: Deliberation and the Social–Technical Divide." *Journal of Risk Research* 18(3):347–363. https://doi.org/10.1080/13669877.2014.971335.

Bickerstaff, K., I. Lorenzoni, N.F. Pidgeon, W. Poortinga, and P. Simmons. 2008. "Reframing Nuclear Power in the UK Energy Debate: Nuclear Power, Climate Change Mitigation and Radioactive Waste." *Public Understanding of Science (Bristol, England)* 17(2):145–169. https://doi.org/10.1177/0963662506066719.

Blue Ribbon Commission on America's Nuclear Future. 2012. "Blue Ribbon Commission on America's Nuclear Future Report to the Secretary of Energy." https://www.energy.gov/sites/default/files/2013/04/f0/brc_finalreport_jan2012.pdf.

Chrisafis, A. 2022. "France to Build U to 14 New Nuclear Reactors by 2050, Says Macron." *The Guardian*, February 10, sec. World news. https://www.theguardian.com/world/2022/feb/10/france-to-build-up-to-14-new-nuclear-reactors-by-2050-says-macron.

Cotton, M. 2021. "Nuclear Power and Environmental Justice: The Case for Political Equality." In *Engaging the Atom: The History of Nuclear Energy and Society in Europe from the 1950s to the Present*, A. Kaijser, M. Lehtonen, M. Rubio-Varas, and J.-H. Meyer, eds. First edition. Energy and Society. Morgantown, WV: West Virginia University Press.

Dignum, M., A. Correljé, E. Cuppen, U. Pesch, and B. Taebi. 2015. "Contested Technologies and Design for Values: The Case of Shale Gas." *Science and Engineering Ethics* 22:1171–1191. https://doi.org/10.1007/s11948-015-9685-6.

DOE (Department of Energy). 2021. "Notice of Request for Information (RFI) on Using a Consent-Based Siting Process to Identify Federal Interim Storage Facilities." *Federal Register* 86(228):68244–68246.

DOE. 2023 "DOE Increases Consent-Based Siting Funding Opportunity to $26 Million." https://www.energy.gov/ne/articles/doe-increases-consent-based-siting-funding-opportunity-26-million.

Downer, J. 2014. "Disowning Fukushima: Managing the Credibility of Nuclear Reliability Assessment in the Wake of Disaster." *Regulation and Governance* 8(3):287–309. https://doi.org/10.1111/rego.12029.

Dryden, R., M.G. Morgan, A. Bostrom, and W. Bruine de Bruin. 2018. "Public Perceptions of How Long Air Pollution and Carbon Dioxide Remain in the Atmosphere. *Risk Analysis: An Official Publication of the Society for Risk Analysis* 38(3):525–534. https://doi.org/10.1111/risa.12856.

Duncan, F. 1990. *Rickover and the Nuclear Navy: The Discipline of Technology*. Annapolis, MD: Naval Institute Press.

EPA (U.S. Environmental Protection Agency). 2013. "Summary of the Nuclear Waste Policy Act." Overviews and Factsheets. https://www.epa.gov/laws-regulations/summary-nuclear-waste-policy-act.

EPRI (Electric Power Research Institute). 2015. *Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Power Generation Facilities (Siting Guide)*. 3002005435. Palo Alto, CA: Electric Power Research Institute. https://www.epri.com/research/products/1006878.

Fischhoff, B., P. Slovic, S. Lichtenstein, S. Read, and B. Combs. 1978. "How Safe Is Safe Enough? A Psychometric Study of Attitudes Towards Technological Risks and Benefits." *Policy Sciences* 9(2):127–152. https://doi.org/10.1007/BF00143739.

Ford, M.J., A. Abdulla, and M.G. Morgan. 2018. "Nuclear Power Needs Leadership, But Not from the Military." *Issues in Science and Technology* 34(4):12.

Gallimore, A.D. 2021. "It's Time for Engineering to Be Equity-Centered." *Inside Higher Ed*, August 30. https://www.insidehighered.com/views/2021/08/30/diversity-equity-and-inclusion-should-be-required-engineering-schools-curricula.

Gamson, W.A. 1987. "Nuclear Forgetting." *Contemporary Sociology* 16(1):15–17.

Harris, J., M. Hassall, G. Muriuki, C. Warnaar-Notschaele, E. McFarland, and P. Ashworth. 2018. "The Demographics of Nuclear Power: Comparing Nuclear Experts', Scientists' and Non-Science Professionals' Views of Risks, Benefits and Values." *Energy Research and Social Science* 46(December):29–39. https://doi.org/10.1016/j.erss.2018.05.035.

Jasanoff, S. 2010. "Ordering Knowledge, Ordering Society." In *States of Knowledge: The Co-Production of Science and Social Order*. International Library of Sociology. London: Routledge.

Kahan, D.M., E. Peters, M. Wittlin, P. Slovic, L.L. Ouellette, D. Braman, and G. Mandel. 2012. "The Polarizing Impact of Science Literacy and Numeracy on Perceived Climate Change Risks." *Nature Climate Change* 2(10):732–735. https://www.nature.com/articles/nclimate1547.

Kasperson, J., R. Kasperson, M. Berberian, and L. Pacenka. 2005. "The Social Contours of Risk: Publics, Risk Communication, and the Social Amplification of Risk." Vol. 1, Earthscan, London.

Keeney, R.L. 1996. *Value Focused Thinking*. https://www.hup.harvard.edu/catalog.php?isbn=9780674931985.

Kemeny, J.C. 1980. "Saving American Democracy: The Lessons of Three Mile Island." *Technology Review* 83(7):65–75.

Leiserowitz, A.A., E.W. Maibach, C. Roser-Renouf, N. Smith, and E. Dawson. 2013. "Climategate, Public Opinion, and the Loss of Trust." *American Behavioral Scientist* 57(6):818–837. https://doi.org/10.1177/0002764212458272.

Markandya, A. 2007. "Electricity Generation and Health." *Lancet* 370(9591):979–990. https://doi.org/10.1016/S0140-6736(07)61253-7.

Mohai, P., D. Pellow, and J.T. Roberts. 2009. "Environmental Justice." *Annual Review of Environment and Resources* 34(1):405–430. https://doi.org/10.1146/annurev-environ-082508-094348.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2022a. *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.

NASEM. 2022b. *Understanding the Societal Challenges Facing Nuclear Power: Proceedings of a Workshop*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26606.

NRC (U.S. Nuclear Regulatory Commission). 1999. *Standard Review Plans for Environmental Reviews for Nuclear Power Plants*. NUREG-1555. Washington, DC: U.S. Nuclear Regulatory Commission.

NRC. 2020. "Consolidated Interim Storage Facility (CISF)." https://www.nrc.gov/waste/spent-fuel-storage/cis.html.

NRC. 2021. "Environmental Justice and the NRC." https://www.nrc.gov/about-nrc/regulatory/licensing/nepa/environmental-justice.html.

Office of Technology Assessment. 1984. *Nuclear Power in an Age of Uncertainty*. OTA-E-216. Washington, DC: U.S. Congress.

Patterson, J.T. 1989. *The Dread Disease: Cancer and Modern American Culture.* Cambridge, MA: Harvard University Press.

Perrow, C. 1999. *Normal Accidents: Living with High-Risk Technologies*. Princeton, NJ: Princeton University Press.

Pew Research Center. 2022. "Public Trust in Government: 1958–2022." https://www.pewresearch.org/politics/2022/06/06/public-trust-in-government-1958-2022.

Roth, E. and G.M. Morgan, B. Fischhoff, L. Lave, and A. Bostrom. 1990. "What Do We Know About Making Risk Comparisons?" *Risk Analysis* 10(3):375–387. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1539-6924.1990.tb00520.x.

Rothman, S., and S.R. Lichter. 1987. "Elite Ideology and Risk Perception in Nuclear Energy Policy." *American Political Science Review* 81(2):383–404.

Saunders, D. 2021. "Opinion: Ten Years Ago, the World Took Away the Wrong Lesson from the Tragedy of Fukushima." *Globe and Mail*, March 6. https://www.theglobeandmail.com/opinion/article-ten-years-ago-fukushima-taught-us-the-wrong-lesson-about-nuclear-power.

Schank, E. 2022. "Poll: Americans, Especially Conservatives, Have Lost Trust in Scientists Since the Pandemic Started." https://www.salon.com/2022/02/17/poll-americans-especially-conservatives-have-lost-trust-in-scientists-since-the-started.

Shellenberger, M. 2019. "It Sounds Crazy, But Fukushima, Chernobyl, and Three Mile Island Show Why Nuclear Is Inherently Safe." *Forbes*, March 11. https://www.forbes.com/sites/michaelshellenberger/2019/03/11/it-sounds-crazy-but-fukushima-chernobyl-and-three-mile-island-show-why-nuclear-is-inherently-safe/?sh=1c6b20871688.

Slovic, P. 1990. "Perception of Risk and the Future of Nuclear Power." *Proceedings of the First MIT International Conference on the Next Generation of Nuclear Power Technology*. http://inis.iaea.org/search/search.aspx?orig_q=RN:37073972.

Slovic, P., B. Fischoff, S. Lichenstein. 1979. "Rating the Risks." *Environment: Science and Policy for Sustainable Development* 21(3):14–39. https://doi.org/10.1080/00139157.1979.9933091.

Starr, C. 1969. "Social Benefit Versus Technological Risk: What Is Our Society Willing to Pay for Safety?" *Science* 165(3899):1232–1238. https://doi.org/10.1126/science.165.3899.1232.

SWI (Swissinfo.ch). 2022. "Will Nuclear Waste Ever Be as Welcome in Switzerland as It Is in Sweden?" https://www.swissinfo.ch/eng/will-nuclear-waste-ever-be-as-welcome-in-switzerland-as-it-is-in-sweden-/47959128.

van de Poel, I., and B. Taebi. 2022. "Value Change in Energy Systems. Science, Technology, and Human Values." *Science, Technology, and Human Values* 47(3):371–379. https://doi.org/10.1177/01622439211069526.

Venables, D., N. Pidgeon, K. Parkhill, K. Henwood, and P. Simmons. 2012. "Living with Nuclear Power: Sense of Place, Proximity, and Risk Perceptions in Local Host Communities." *Journal of Environmental Psychology* 32(December):371–383. https://doi.org/10.1016/j.jenvp.2012.06.003.

Weart, S.R. 1988. *Nuclear Fear: A History of Images*. Cambridge, MA: Harvard University Press.

Weinberg, A.M. 1972. "Social Institutions and Nuclear Energy." *Science* 177(4043):27–34.

Weinberg, A.M. 1976. "The Maturity and Future of Nuclear Energy." *American Scientist* 64:16–21.

Wynne, B. 1991. "Knowledge in Context." *Science, Technology and Human Values* 16(1):111–121.

Wynne, B. 1992. "Misunderstood Misunderstanding: Social Identities and Public Uptake of Science." *Public Understanding of Science* 1(3):281–304.

9

Ensuring Security and Promoting Safeguards

Security, safeguards, and safety all focus on the reduction of risk and the protection the environment and society from release or loss of regulatory control of radioactive materials. Security seeks to address intentional threats (e.g., malicious events such as theft, sabotage, insider threats, cyber-attacks, terrorism) and the consequences of such events. Safeguards cover a specific aspect of security by addressing threats of diversion of special nuclear material[1] from legitimate civilian applications by a State actor for the purpose of weapons development.[2] Safety addresses the risk of accidental events (such as natural hazards, equipment failures, or human error). Safety, security, and safeguards are often discussed together as the "3S's." This report discusses safety in the context of advanced reactor designs (see Chapter 2) and of U.S. Nuclear Regulatory Commission (NRC) regulatory requirements (see Chapter 7). Security and safeguards are the focus of this chapter.

Future nuclear power reactors deployed in the United States or internationally will have to demonstrate that they are secure from malicious threats, both physical and cyber. New and advanced reactors deployed in non-nuclear weapons states will also need to demonstrate that nuclear material and information are protected from diversion and misuse for nuclear weapons. This chapter describes the means that support the security of civilian nuclear power facilities and that ensure proper safeguarding of nuclear material and information within a nuclear facility.[3] The committee highlights the challenges of ensuring security and safeguards at new and advanced reactors and their new deployment scenarios and provides recommendations.

SECURITY

Security in the United States is regulated by the NRC in 10 CFR Part 73 and in the case of power reactors is reflected in a series of plans: a Physical Security Plan, a Training and Qualification Plan, a Safeguards Contingency Plan, and a Cyber Security Plan.[4] The committee focuses first on physical security.

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[1] Special nuclear material includes plutonium, uranium-233, and uranium enriched in the isotope uranium-233 or in the isotope uranium-235. The definition can be expanded by the NRC to include other nuclear materials, but the NRC has not done so.

[2] This description of safeguards is consistent with international safeguards, implemented by the IAEA. U.S. domestic material control and accounting (MC&A) measures aim to ensure nuclear materials are not diverted for any use, and IAEA international safeguards aim to ensure that nuclear materials are not used in the development of weapons by State actors, in accordance with international non-proliferation treaties.

[3] The terms used here, nuclear power facilities and nuclear facility, highlight that security and safeguards are applied to the broader nuclear facility complex and not simply the nuclear reactor.

[4] See U.S. Nuclear Regulatory Commission Regulations, n.d., "Title 10, §73.55(a)" in *Code of Federal Regulations*, Washington, DC: Government Publishing Office and National Archives and Records Administration.

Physical Security

The security framework applicable to reactors is designed to protect against a design basis threat (DBT) of radiological sabotage.[5] In the case of existing large LWRs, the security framework is designed to prevent significant damage through sabotage of the core and spent fuel. The DBT is based on current assessments of the tactics, techniques, and procedures of international and domestic terrorist groups and organizations. The specific details of the DBT are not publicly available, but, in general, the DBT outlines threats and adversary characteristics against which a licensee must demonstrate it can defend its facility.[6] In addition, other open-source information on current and potential threats could impact the development and deployment of new and advanced reactors.[7]

Nuclear power plants (NPPs) are, by design and construction, difficult to penetrate. Security at existing NPPs is subject to detailed prescriptive regulation.[8] The combination of robust structures that are difficult to penetrate, a well-armed professional security force, intrusion detection, strict access controls for workers and visitors, and multiple backup safety systems provides multiple layers of security.

Physical security is based on three concentric circles, with the level of security increasing as one gets closer to vital equipment. The large outer perimeter, called the "owner-controlled area," is far enough from the reactor that only minimal security is needed. The "protected area" is fenced and protected by sophisticated security systems and armed security officers. The innermost circle is called the "vital area." It contains the reactor and associated safety systems, the control room, the used fuel pool, and the security alarm stations. Access to the vital area is limited and protected by locked and alarmed security doors. The NRC requirements also cover protections against insider threats, continuous communication capability, lighting, electronic surveillance and physical patrols of the plant perimeter and interior structures, robust barriers to critical areas, and background checks and access control for employees, among many other elements. In addition, each plant has an integrated security and response plan with federal, state and local law enforcement agencies. The security plan is subject to inspection, as well as triennial "force-on-force" exercises to verify its effectiveness. The NRC is required to provide an annual report to the Congress in both classified and unclassified form of the results of each security evaluation and of any resulting corrective actions. The unclassified report is widely available. 42 USC 2010d.

The advanced reactor designs and deployment scenarios are far different from conventional nuclear power reactors. For example, some of the reactor designs have features that might decrease security risk and justify modification of some of the physical protection requirements. These features include the following:

- **Smaller source term.** Some of the designs have smaller power outputs in comparison to operating large LWRs, with a correspondingly smaller inventory of fission products; of course, if multiple units are sited at one location, the total source term will have to be evaluated.[9]

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[5] See U.S. Nuclear Regulatory Commission Regulations, n.d., "Title 10, §73.1 and §73.55" in *Code of Federal Regulations*, Washington, DC: Government Publishing Office and National Archives and Records Administration.

[6] See U.S. Nuclear Regulatory Commission Regulations, n.d., "Title 10, §73.1(a)" in *Code of Federal Regulations*, Washington, DC: Government Publishing Office and National Archives and Records Administration.

[7] See, for example, Office of the Director of National Intelligence, 2022, "Annual Threat Assessment of the U.S. Intelligence Community," *Office of the Director of National Intelligence*, https://www.dni.gov/files/ODNI/documents/assessments/ATA-2022-Unclassified-Report.pdf. For a review of methods for proliferation risk assessment, see National Research Council, 2013, *Improving the Assessment of the Proliferation Risk of Nuclear Fuel Cycles*, Washington, DC: The National Academies Press. https://doi.org/10.17226/18335.

[8] See U.S. Nuclear Regulatory Commission Regulations, n.d., "Title 10, §73.55" in *Code of Federal Regulations*, Washington, DC: Government Publishing Office and National Archives and Records Administration.

[9] Note that the advantage of less fuel in a given unit is reduced if the deployment involves multiple individual units comprising a single power generating facility.

- **Design features aimed at reducing vulnerabilities.** Many of advanced reactors use simplified, inherent, and/or passive design features that reduce the vulnerabilities that might be exploited by an attacker.
- **Underground protection.** Housing the reactor below ground level, as some designs have done, could limit access to vital equipment by an intruder and protect the plant from an aircraft attack.

However, some of the designs and deployment scenarios (see Chapter 2) increase security risks and present new security challenges, including:

- **Remote operation.** Advanced reactors deployed to remote regions of the United States and the world that have minimal existing security infrastructure may require additional active and passive delay elements that increase task completion times for malicious actors (Evans et al. 2021a). Remote operations also raise unique challenges regarding cyber security (see the next section).
- **Reduced staffing.** Some operating models propose smaller numbers of on-site security staff, compared to conventional nuclear power facilities. Fewer on-site staff may reduce the potential insider threat for the facility, but also may reduce the capability to repel an attacker. (Duguay 2020).
- **Security of fuels.** Some of the new and advanced reactors rely on high assay low-enriched uranium (HALEU) fuel,[10] which is more attractive for diversion or theft than LEU and may require additional security measures. Other designs require recycling of spent fuel, creating opportunities for diversion or theft of weapons-usable fissile materials.
- **Transportable facilities.** Some designs allow for the transport of the nuclear power facility with its fuel, such as some microreactor designs (see Chapter 7). Security guidance exists for transporting nuclear materials, which have different threats and physical security measures than for materials stored in a stationary and secure location (IAEA 2015).[11]

The NRC has engaged with reactor vendors and other stakeholders with regard to the physical security requirements appropriate to advanced reactors and in 2018 the Commission approved the commencement of a limited scope rulemaking that, while retaining the current overall physical security framework, would provide specific alternative requirements that could be applied at advanced reactors (NRC 2018). In August 2022 the NRC staff sought authorization from the Commission to publish a proposed rule that would offer voluntary performance-based alternatives for meeting certain physical security requirements for advanced reactors (NRC 2022). The proposed rule would make available alternative performance-based requirements for applicants and licensees that meet a proposed eligibility criterion. That criterion would require a demonstration that the consequences of a postulated release arising from a security-related event do not exceed a specific offsite dose limit.[12] That is, the proposed

[10] High-assay LEU (or HALEU) is uranium enriched in U-235 between 5 percent and 20 percent. Although HALEU above 10 percent enrichment is subject to stronger security than LEU (10 CFR 73.2), it cannot be used in a nuclear weapon absent further enrichment. As a result, the concerns about HALEU focus on the potential to use HALEU as enrichment feedstock to produce high-enriched uranium (HEU), which is typically enriched to 90 percent or greater in a nuclear weapon.

[11] See National Academies of Sciences, Engineering, and Medicine. 2023. *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.

[12] The dose limit for an individual on the outer boundary of the exclusion area is 25 rem total effective dose equivalent (TEDE) over any 2-hour period and 25 rem for an individual located at any point on the outer boundary of the low population zone. See U.S. Nuclear Regulatory Commission Regulations, n.d., “Title 10, §50.34(a)(1)(ii)(D)” in *Code of Federal Regulations*, Washington, DC: Government Publishing Office and National Archives and Records Administration.

changes would be available only if the offsite consequences of a radioactive release from the facility are limited.

The alternative security arrangements for eligible applicants have the following elements:

- The licensee would be relieved from the requirement to provide a minimum number of armed responders (currently a minimum of 10 is required), potentially allowing no onsite armed responders.
- The licensee could rely on law enforcement (local, State, or Federal) or other offsite armed responders rather than using armed onsite licensee security personnel. The licensee would still be required to show the capacity of detect, assess, interdict and neutralize threats up to the level defined by the DBT.[13]
- The licensee would be allowed to apply means other than physical barriers to achieve the intended delay functions for armed security responses. These means might include the use of engineered systems (e.g., obscurants, irritants, slippery agents) and/or human actions.[14]
- The licensee would be allowed to locate the secondary alarm station offsite.
- If the licensee were to locate the secondary alarm system offsite, it would not be required to designate the secondary alarm station as a vital area and locate the secondary power supply for the secondary alarm station as a vital area.

The path to a final rule governing security for advanced reactors is likely to be a long one. The proposed rule will be released for public comment only after Commission review and possible modification. Then after comments are received and any changes to the proposed rule are made, the final rule must again receive Commission approval before promulgation. It then might undergo review in the courts. In the meantime, the staff has indicated that it will prepare guidance to explain the demonstrations that it would require from an applicant seeking to apply the new requirements.

Once the tailored approach framework is in place, the NRC will require advanced reactor vendors to validate their claims about adequate security, especially for applications that include significant reductions in on-site security staff or the use of novel technologies to enhance site-security, such as increased reliance on integrated sensors, automated barriers, or drone systems for detection and response. Such validation would likely require a combination of path analysis adversary modeling and evaluation of accident progression scenarios most applicable to the wider range of deployment options that some vendors envision.

Findings and Recommendations

Finding 9-1: The U.S. Nuclear Regulatory Commission (NRC) staff has proposed significant modifications to physical security requirements to accommodate designs and operations proposed by licensees of advanced reactors that differ from larger light water power reactors. There are many hurdles, including new assessments without clear NRC guidance on compliance

[13] The Department of Energy Order 151.1 requires DOE to establish an emergency management system (DOE 2023). In response, DOE has developed a set of emergency response guidelines and training programs together with contractors, state, tribal, and local jurisdictions. One program is focused on transportation emergency preparedness (Transportation Emergency Preparedness Program 2023). While recognizing that federal agency's responsibilities are different from a licensee's obligations, there may still be lessons learned or materials of use in DOE's emergency preparedness programs for licensees of advanced reactors.

[14] Some early studies on physical protection requirements for advanced reactors and their deployment scenarios have indicated that the proposed facility design scenarios would benefit from additional protections (Evans et al. 2021a), such as: additional and hardened exterior walls, hardened doors, installation of multiple mantraps/airlocks, and obscurants. Other methods for increasing physical protection not analyzed in Evans et al. 2021a include the use of drones for monitoring and response, integrated sensors, and automated barriers.

demonstrations and a fuller understanding of the vulnerabilities that the new designs and deployment scenarios may present. These issues must be evaluated and any capacity/capability shortfalls in NRC expertise must be overcome before any such modifications can be applied by vendors.

Recommendation 9-1: The modification of the security requirements proposed by the U.S. Nuclear Regulatory Commission (NRC) staff could have significant implications for the design, staffing, and operations of advanced reactors, thereby impacting business plans. Delays in providing clear regulatory guidance may impact capital availability and increases the potential for costly redesign if guidelines do not align with expected modifications to existing protocols. Congress should provide additional funding for NRC evaluation of security guidelines and NRC should expedite its consideration of the staff proposal and seek to complete the rule making promptly if significant changes are deemed appropriate. In that case, the prompt completion of the associated guidance should also be a high priority.

Cyber Security Challenges

NPPs are monitored and controlled through a collection of instrumentation and control (I&C) systems including reactor protection and control systems, secondary plant control systems, and (reactor) health monitoring systems. The design of individual I&C systems for reactor control and protection is directly correlated to the type and design of the reactor and its related safety systems. New designs for advanced nuclear reactors envision "passive" safety and control systems that would function without the need for external sources of power or control but would still require an operable I&C system with accurate inputs to monitor conditions.

Licensees of NPPs are required to have a cybersecurity plan that meets requirements laid out in 10 CFR 73.54. These requirements ensure that the functions of critical systems and digital assets are protected from cyberattack throughout the system engineering life cycle, using a graded approach.[15] Guidelines for complying with the 10 CFR 73.54 requirements are spelled out in NRC Regulatory Guide 5.71 (NRC 2010).[16] Each advanced reactor vendor is required to develop a cybersecurity plan and maintain a cybersecurity program as part of security protocols.

Advanced reactor vendors face significantly different challenges than the designers of the existing LWR fleet. Increased use of automation, wireless sensors and controls, and digital management of a complex operations and supply chain may create opportunities for reducing human error in such systems. They also mean that the threat spectrum may be significantly enhanced in some respects for the new design. Ultimately, because of this new and growing risk category, there will certainly be increased scrutiny from the NRC in licensing and ongoing assessment/regulation of these new control, protection and asset management systems.[17]

The Nuclear Energy Institute (see NEI 08-09, Revision 6) has provided further guidance targeted to new vendors to help them address the multiple challenges they face in meeting cyber guidelines (NEI 2010 2016). It will be vital for each vendor to ensure that their security plans address the threat/attack pathways as they apply to their specific designs. They must also continuously evaluate risk and update their security protocols and system upgrades as appropriate, as spelled out in 10 CFR 73.54, to ensure all

[15] The IAEA defines "graded approach" as: a structured method by which the stringency of control to be applied to a product or process is commensurate with the risk associated with a loss of control (IAEA 2014).

[16] The Regulatory Guide provides an approach for complying with the requirements outlined in 10 CFR 73.54. See U.S. Nuclear Regulatory Commission, 2010, "Regulatory Guide 5.71: Cyber Security Programs for Nuclear Facilities," https://www.nrc.gov/docs/ML0903/ML090340159.pdf.

[17] See, for example, NRC, 2008, "Instrumentation and Controls in Nuclear Power Plants: An Emerging Technologies Update," NUREG/CR-6992.

cyber threats are mitigated. Although digital I&C offers the promise of reduced staff and reduced vulnerability to some types of human error, and thereby reduced costs, the need to ensure cybersecurity could impose different new operating costs and can introduce new accident vulnerabilities. Claimed cyber security protocols must be tested and regularly validated. Vendors must incorporate sufficient cybersecurity controls to ensure safety and guarantee asset protection and manufacturing facility protection across the product life cycle.

Findings and Recommendations

Finding 9-2: Advanced reactor designers envision increased use of automation and the potential for use of artificial intelligence–enabled sensors and controls to reduce staff costs, enhance the robustness of defenses, and, in some cases, provide for remote, multi-asset operations. These systems could increase cybersecurity risk, with some resulting security cost burden over the operating life of the reactor.

Recommendation 9-2: The U.S. Nuclear Regulatory Commission (NRC) must ensure the safety and security of new designs, especially for designs that employ greater automation and incorporate remote operating options. Claimed cybersecurity protocols should be tested and regularly validated across the full life cycle of the facility. Licensees should incorporate sufficient cybersecurity controls to ensure safety and guarantee asset protection and manufacturing facility protection across the product life cycle. Both the NRC and the vendors should work closely with the International Atomic Energy Agency's Small Modular Reactor and Instrumentation and Control Systems groups to develop international standards and determine whether new monitoring alternatives are needed.

SAFEGUARDS

The term *safeguards* refers to the monitoring of nuclear material and information to reduce the risk of diversion of special nuclear material. In the United States, the NRC has a set of regulations via 10 CFR Part 74 that require licensees to establish, maintain, and provide reporting of special nuclear material through material control and accounting (MC&A) measures, serving both a safeguards and security purpose.[18] Internationally, the term *safeguards* refers to "a set of technical measures applied by the [International Atomic Energy Agency] on nuclear material and activities, through which the Agency seeks to independently verify that nuclear facilities are not misused and nuclear material not diverted from peaceful uses [by State actors]" (IAEA 2016). The IAEA independently establishes and monitors the MC&A measures for the nuclear facility (Garrett et al. 2021, pp. ii–iv). United States vendors will need to incorporate both types of MC&A measures into their facilities and processes if they plan to market their systems both in the United States and internationally. The additional elements imposed by the IAEA include surveillance and monitoring equipment accessible by the IAEA to verify that nuclear material has not been diverted.

Under current international standards, each nation bears the responsibility for securing nuclear (and other radiological) materials and relevant facilities and activities within their borders. The IAEA and its state parties identify specific sets of measures for protecting nuclear materials and information through safeguards agreements. As a recognized nuclear weapons state under the Treaty on the Non-Proliferation of Nuclear Weapons ("NPT"), the United States is not required to conclude a safeguards agreement with

[18] As noted in an earlier footnote, U.S. domestic material control and accounting (MC&A) measures aim to ensure nuclear materials are not diverted for any purpose. IAEA international safeguards aim to ensure that nuclear materials are not used in the development of weapons by State actors, in accordance with international non-proliferation treaties.

the IAEA. Non-nuclear weapons States that have entered into the NPT, and in some instances groups of nations (e.g., EURATOM, the European Atomic Energy Community, enter into safeguards agreements with the IAEA to allow verification of compliance with the NPT (IAEA 2002). Although the United States has no obligation to accept IAEA safeguards under the NPT, the U.S.-IAEA Voluntary Offer Agreement (as implemented through 10 CFR Part 75) allows a small number of domestic facilities to be subject to international safeguards and inspection by the IAEA. The advantages are two-fold: to allow the IAEA to gain experience in implementing new safeguards technologies and in testing of new safeguards equipment, and to demonstrate that the United States is willing to follow the same rules as the non-nuclear weapons states.

Advanced reactors present new MC&A and safeguards challenges because they use new fuels and fuel cycles, new reactor designs, longer operation cycles, new supply arrangements, new spent fuel management, diverse operational roles, and unattended monitoring systems (Cipiti 2022). Some safeguards and materials control and accounting challenges will also depend on the design and location of the facility, such as deployments in remote locations.

The U.S. companies currently developing advanced reactors are taking substantially different technical approaches in their designs. At the same time, most U.S. nuclear facilities are not subject to safeguards requirements, so many in the U.S. nuclear industry are not fully familiar with these requirements. In some cases, new sensors and other instrumentation need to be developed and commercialized to enable a successful safeguards strategy.[19] These safeguards strategies, reflecting both national and international safeguards obligations, will likely reflect a balance of different risks and rewards. For example, some designs call for less frequent refueling (a more proliferation-resistant design element) but use higher enriched fuels, such as HALEU (a less proliferation-resistant design element).

The most significant safeguards technology gaps exist for continuously fueled reactors (e.g., liquid-fuel reactors), such as molten salt reactors. During operation, the actinides and fission products are contained within a liquid salt, which serves as both fuel and primary coolant for molten salt reactors. Some actinides and fission products are dissolved within the salt, and others exist as colloidal particles. The isotopic concentration of these products changes continually over time.[20] Furthermore, the salt may not be strictly homogeneous—the concentrations of materials may vary throughout the primary loop, for example as a function of temperature. Additionally, the coolant used in liquid fueled reactors (and in reactors that employ lead or sodium as a coolant) is opaque. Simply put, the use of continuous fuel changes the nature of the MC&A and safeguards requirements by effectively combining a nuclear reactor, a fuel fabrication facility, and a fuel reprocessing facility. Adding to these challenges, the operational temperature and radioactivity of a continuous fueled reactor, require MC&A and safeguards instrumentation to survive and operate reliably in harsh environments.

One potentially positive aspect of these challenging safeguards conditions is that molten salt and other liquid fuels increase the technical sophistication that would be required to divert material, requiring specialized equipment for processing and transport, thereby making diversion challenging, dangerous, and costly (Prasad et al. 2015). To exploit this advantage, however, the technical safeguards solutions must be validated and must prove reliable, which could lengthen regulatory timelines.

MC&A and safeguards difficulties also exist in systems using pebble fuel.[21] In a pebble bed reactor, for example, the different fuel pebbles cannot be distinguished from one another, and currently do not have specific serial numbers, so the pebbles are considered to be a bulk material (Boyer et al. 2010).

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[19] For example, pebble bed and liquid fueled reactors may require new sensors and instrumentation for material inventory control.

[20] The isotopic content evolves during reactor operation owing to four main processes: (1) plate-out of noble and semi-noble metals, (2) active removal of gaseous fission products, (3) online reprocessing of fuel salt, and (4) online refueling.

[21] Pebble fuels, such as TRISO particles, are seen as having higher proliferation resistance as compared to traditional reactor fuels owing to the small amount of U-235 within each pebble and the difficulty of extracting U-235 from the pebble's matrix (Cheng 2021).

Fortunately, the IAEA has experience in applying safeguards at pebble bed reactors in Germany (AVR and THTR-300, no longer operating, see Martin 1987) and China (HTR-10, operating since 2004, and HTR-PM, operating since December 2021). However, the IAEA has no prior safeguards experience with molten salt reactors. IAEA's experience from establishing safeguards at an aqueous reprocessing facility, the Rokkasho Reprocessing Plant in Japan, and at fuel fabrication and bulk facilities may be relevant for any future work at molten salt reactors (Garrett et al. 2021).[22]

Enhancing advanced reactor safeguards, especially for the particularly challenging case of continuous liquid fueled systems, requires addressing some key technology gaps.[23] Pebble bed reactors will require measuring the final isotopic content when pebbles may have differing burnup histories or different initial enrichment levels, requiring the advancement of technologies such as radioisotope pebble tagging, predictive pebble tracking, burnup estimation, and NDA techniques.[24] For continuous liquid fueled reactors, instrumentation capable of making the following measurements is needed:[25]

- Determining isotopic composition of the liquid fuel, considering potential inhomogeneity
- Volume of salt in key areas: reactor core, pumps, processing tanks, storage tanks
- Identification of volumetric changes (deliberate or unintentional) as a function of time
- Materials flow monitoring
- Isotopic composition of gases.

Robust measurement instrumentation for pebble bed and continuously liquid fuel reactors does not yet exist but is needed to provide accurate measurements of inventories in materials balance areas and track the flow of materials throughout the plant.

Efforts within the United States and the IAEA are in the early stages of exploring potential approaches that would provide the IAEA and regulatory authorities with greater assurance when making safeguards determinations such as: continuous on-line enrichment monitoring, satellite imagery analysis, remote data transmission, and environmental sampling (Maceda et al. 2022).

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[22] For proposed domestic safeguards for pebble-bed reactors, see D. Kovacic, P. Gibbs, and L. Scott, 2020, Model MC&A Plan for Pebble Bed Reactors, Letter Report for Technical Direction #5 Task 2.6 (ORNL/SPR-2019/1329), https://info.ornl.gov/sites/publications/files/pub132501.pdf.

[23] See the following research papers and presentations related to R&D on MSR MC&A and safeguards technology: D.E. Holcomb, R.A. Kisner, and S.M. Cetiner, 2018, Instrumentation Framework for Molten Salt Reactors, ORNL-TM/2018-868, https://info.ornl.gov/sites/publications/Files/Pub111607.pd ; M. Croce, K. Koehler, K. De Castro, et al., 2020, Experimental Validation of Nondestructive Assay Capabilities for MSR Safeguards, https://gain.inl.gov/SiteAssets/2021-April_SafeguardsAndSecurityWorkshop/Reading/Experimental%20Validation%20of%20NDA%20for%20MSR%20Safeguards%20FY20%20Report.pdf; A.M. Lines, H.M. Felmy, A.S. Medina, et al., 2020, Evaluation of optical techniques for molten salt reactor materials control and accounting, Pacific Northwest National Laboratory, https://gain.inl.gov/SiteAssets/2021-April_SafeguardsAndSecurityWorkshop/Reading/Evaluation%20of%20Optical%20Techniques%20for%20Molten%20Salt%20Reactor%20Materials%20Control%20and%20Accounting%20-%20PNNL.pdf ; N. Hoyt and C. Moore, 2021, Flow Enhanced Electrochemical Sensors for Molten Salt Reactors, Argonne National Laboratory, https://gain.inl.gov/SiteAssets/2021-April_SafeguardsAndSecurityWorkshop/Presentations/Safe_Secure_Day3_Website/04-Flow%20Enhanced%20Electrochemical%20Sensors%20for%20MSRs-Hoyt.pdf.

[24] List from the Garrett et al. 2021, p. 33.

[25] Notably, the IAEA safeguards approach developed at Rokkosho resulted in more than 50 monitoring and measuring systems plus dozens of cameras required to track assemblies, measure and monitor radioactive solutions, and verify the final product and waste streams (Garret et al. 2021, p. 37).

Findings and Recommendations

Finding 9-3: As advanced reactors continue to be developed with the potential of rapid scale-up both domestically and internationally in the coming decades, it is crucial to recognize, prioritize, and address potential gaps in safeguards technology and to incorporate key measurement capabilities at the earliest stages of the design process. Several initiatives in the United States and within the International Atomic Energy Agency have begun to address these challenges.

Recommendation 9-3: The International Atomic Energy Agency (IAEA) and Department of Energy (DOE) should identify the funding, personnel, regulatory analyses, and key technology gaps for pilot programs in international safeguards for advanced reactors. There is also a need for the vendors to engage early in their designs to fully understand IAEA safeguards requirements and implementation. Because the first vendors will bear the largest cost burden in developing and implementing safeguards for new advanced reactor designs that other vendors may incorporate, the IAEA and DOE should develop cost incentive-based programs to encourage early-adopter vendor participation in safeguards development.

SAFETY, SECURITY, AND SAFEGUARDS BY DESIGN

There is an important interface between safety, security, and safeguards—the 3Ss. In some instances, risk reduction efforts in one domain reduces risks in all three. Controlling access to nuclear materials at a nuclear facility, for example, helps limit accidental exposures to radiation (safety), prevents theft (security), and prevents the sabotage of seals or surveillance devices (safeguards). In other instances, however, reducing risks in one domain increases risks in others. For security purposes, for example, facilities may want to delay potential attackers, which can increase the barriers for rapid access by emergency services in case of an accident or limit the activities of safeguards inspectors.[26] Efficient and effective nuclear facility design is best achieved when requirements from the 3S disciplines are anticipated and intrinsic to the facility design. In that way the implications of a design element on each of the 3Ss can be evaluated and appropriate tradeoffs, if necessary, can be made.

The failure to consider the implications of each domain on the others from the outset of design is likely to increase both capital and operating costs and may limit the effectiveness of the response to 3S challenges. The appropriate balance can be achieved through an understanding of the requirements in each arena and considering them during all phases of the design process (Snell 2013). 3S by design from the earliest stages promises to avoid costly retrofitting of reactor designs and facilities. For example, enhanced security requirements were imposed on the fleet of operating nuclear reactors as a result of the 9/11 attack. The need to back-fit enhanced security features on established plants led to significant capital expenditures and increased operating costs.

New and advanced reactors will not be immune to the 3S challenge. The IAEA held a webinar on the topic in February 2022, and a technical meeting on 3S in the design of SMRs in June 2022 (IAEA 2022a, Iturria and Li 2022). Participants in the technical meeting recognized that more must be done to raise awareness about the 3Ss, especially for security and safeguards issues compared to the better-known safety issues and recommended that the IAEA provide guidance on 3S by design for SMRs and take a more holistic 3S approach to its work (Iturria and Li 2022). U.S. vendors would benefit from participating in the development of 3S-by-design guidance, along with developments in security-by-design and safeguards-by-design, such as the early work by the IAEA on increased regulatory collaboration or the

[26] The complications from the interface between safety and security have attracted more attention than the interface with safeguards. See, for example, IAEA (2010).

efforts to promote standardization of advanced reactor manufacturing, construction, and operation (Liou 2022b).

Finding 9-4: Consideration of safety, security, and safeguards requirements—individually as well as their interactions—at the beginning of and throughout the advanced reactor design process by the vendors will avoid unnecessary costs and complications.

Recommendation 9-4: Vendors bear the responsibility of demonstrating compliance of their designs with safeguards, security, and safety requirements, including International Atomic Energy Agency safeguards requirements for reactors sold to non-weapons states. Vendors should recognize that these requirements are interrelated with each other and should ensure that any necessary trade-offs are made early in the design process.

CURRENT U.S. GOVERNMENT AND IAEA INITIATIVES

Both the U.S. government and IAEA have developed programs promoting security and safeguards within advanced reactor designs and deployments.[27] Historically, the United States has created partnerships with several countries, such as Japan and the Republic of Korea, that have adopted high standards for safeguards and security. Given the potential for increased deployment of nuclear reactor systems around the world to address climate change, the U.S. Congress has supported—and in some cases mandated—increased support of U.S. efforts focused on security and safeguards by DOE and the NRC. In earlier chapters of this report, DOE-NE's programs and investment in advanced nuclear have been discussed as well as the NRC's international engagement (see Chapter 7). Here the committee focuses on programs targeted for implementation of security and safeguards in the international deployment of advanced reactors.

U.S. Government Initiatives

Defense Nuclear Non-proliferation (DNN) (through the NNSA Office of Non-Proliferation and Arms Control) has established the Advanced Reactor International Safeguards Engagement (ARISE) program with an international focus and the Advanced Reactor Safeguards (ARS) program with a U.S. domestic R&D focus.

ARISE supports effective and efficient IAEA safeguards implementation by engaging with the U.S. advanced reactor community to educate stakeholders on IAEA safeguards and promote timely incorporation of international safeguards by design (DOE-NNSA 2017, 2022). A congressionally mandated program, ARISE connects vendors with DOE national laboratory experts to assist with incorporating international safeguards by design into early design development.

The ARS program applies laboratory R&D to address near-term challenges advanced reactor vendors face in meeting U.S. domestic safeguards (Material Control and Accounting [MC&A] and Physical Protection System [PPS] requirements [Cipiti 2021, slide 2; Cipiti 2022]). ARS has the following thrust areas:[28]

- Thrust Area 1: Developing a Robust and Cost-Appropriate Physical Protection Systems (PPS)
- Thrust Area 2: Develop MC&A Approaches for Pebble Bed Reactors

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[27] Both DOE-NNSA and the IAEA have gathered sets of documents to guide safeguards by design development efforts. DOE-NNSA guidance at: https://www.energy.gov/nnsa/downloads/safeguards-design-guidance-documents; IAEA guidance at: https://www.iaea.org/topics/assistance-for-states/safeguards-by-design-guidance.

[28] For the most recent reports for each thrust area see Gateway for Accelerated Innovation in Nuclear, 2023, "Advanced Reactor Safeguards," https://gain.inl.gov/SitePages/ARS.aspx.

- Thrust Area 3: Determine MC&A and PPS Requirements for Microreactors
- Thrust Area 4: Develop MC&A Approaches for Molten Salt Reactors
- Thrust Area 5: Leverage International Interfaces

The ARS program has released a number of useful reports within each thrust area and referenced throughout this chapter. The committee agrees with the following statement made in *Advanced Reactor Safeguards: Lessons from the IAEA Safeguards Domain*:

> A final general need area is for advance coordination and information sharing between stakeholders. As mentioned previously, the specific domestic MC&A and IAEA safeguards needs will likely vary for different facility types, and domestic and international requirements will continue to evolve. Coordination at appropriate intervals involving facility designers, U.S. government stakeholders (including DOE/NNSA) and the IAEA will help identify problems proactively and help navigate interfaces between domestic MC&A and IAEA safeguards. This is particularly true for facilities such as liquid-fueled MSRs that may have especially complex MC&A systems. (Garrett et al. 2021, p. 42)

Support provided to vendors under these DOE NNSA programs is typically coordinated through the U.S. National Laboratory System. To ensure the protection of vendor intellectual property, the individual engagements generally include a non-disclosure agreement. In order to simplify engagement, DOE NNSA has also developed an online presence, U.S. Nuclear Nexus to support safeguards and security engagement.[29] The U.S. national laboratories also have considerable experience in working with international partners and could offer lessons learned to all stakeholders on the infrastructure for cooperative ventures, especially on a range of knowledge management issues, such as export controls, intangible technology transfers, collaborating and hosting foreign nationals, and visa conditions.

DOE has also enhanced cross-domain research and development that will enable more rapid development efforts through a new program called “ANSWER” (an acronym for Advanced Nuclear Security, Waste and Energy R&D). ANSWER is supported by the DOE Offices of Science and Nuclear Energy and the NNSA (Lauren-Kovitz 2021). ANSWER’s working groups, consisting of a core group and technical subgroups, is the primary mechanism for addressing specific challenges. One of the initial technical subgroups is titled, “Incorporating Safeguards and Security by Design into Advanced Reactor and Fuel Cycle Technologies,” with an objective to “identify and resolve technical, regulatory, and policy challenges related to safeguards and security for advanced reactor and fuel-cycle technologies early in the design process and in close coordination with industry” (Lauren-Kovitz 2021, slide 6). Priority actions for the subgroup are (Lauren-Kovitz 2021, slide 6):

1. Ensure necessary technical and policy support for U.S. vendors to complete physical protection design parameters for submission to NRC.
2. Provide technical basis for advanced reactor and fuel cycle (e.g., Molten Salt Reactor, Pebble Bed, and Microreactor) materials accountancy system design and vital area/target set identification techniques.
3. Support engagement between U.S. vendors and the IAEA to ensure that international safeguards and security requirements and best practices are incorporated into reactor designs.

The committee was not told which vendors were engaging with DNN programs or ANSWER initiatives.

IAEA Initiatives

Multilaterally, the IAEA offers a range of technical assistance to its Member States on nuclear safeguards and security, which has increased considerably over the past two decades. Most notable are its

[29] See U.S. Nuclear Nexus, 2023, “Your resource to engage with NNSA on global deployment of the U.S. civilian nuclear technology,” https://nuclear-nexus.nsis.anl.gov/nexus.

growing list of Nuclear Security Series guidance documents and the use of IAEA Integrated Nuclear Security Support Plans (INSSPs), where, upon request of the Member State, the IAEA helps identify and prioritize where a State may need to strengthen its national nuclear security regime, following the Nuclear Security Series Guidance, along with other relevant input, such as recommendations from International Physical Protection Advisory Service (IPPAS) and International Nuclear Security Advisory Service missions. More than 100 IAEA Member States have INSSPs under implementation or finalized (IAEA Director General 2021). The IAEA also maintains a Nuclear Security Information Portal (NUSEC), supports the work of national Nuclear Security Training and Support Centres (NSSCs) and the International Security Education Network (INSEN), maintains an Incident and Trafficking Database (ITDB), conducts dozens of national security training projects annually, and has developed several on-line nuclear security training modules (IAEA Director General 2021). Requests for assistance on nuclear security have increased, especially after the entry into force of the Amendment of the Convention on the Physical Protection of Nuclear Material (A/CPPNM) in 2016, prompted the IAEA to begin construction of its first Nuclear Security Training and Demonstration Centre in July 2021, with more than €11 million in extra-budgetary funding pledged from Saudi Arabia, the United Kingdom, and the United States (IAEA 2021b).

The increased role of nuclear security in IAEA activities has spread to encompass the IAEA's work on new and advanced reactors. In 2015, the IAEA established a SMR Regulator's Forum focused on licensing and safety issues, supplemented by the formation of a Technical Working Group on Small and Medium Sized or Modular Reactors (TWG-SMR) in 2018.[30] In 2021, the IAEA began a nuclear security project for SMRs for the sharing of information on SMR security systems and how requirements and guidance from the Nuclear Security Series can apply to SMRs. This project will form the basis of future Series documents and training programs (IAEA Director General 2021).

The current regular budget for IAEA nuclear security and safeguard activities is €6.4 million for nuclear security and €133.5 million for safeguards implementation (IAEA 2020). The IAEA Division of Nuclear Security relies on extra-budgetary funding five or six times the amount of the regular budget to conduct its work (GAO 2019). Furthermore, the zero-growth constraints on the IAEA budget (IAEA 2022b, p. iii; GAO 2019, p. 10) and an unwillingness by some IAEA Member States to reapportion the budget from other activities (see GAO 2019, pp. 30–32) will impair efforts to make deployment of new and advanced reactors safeguarded and security without significant changes in the current funding stream. These initiatives that aid potential partners for deploying U.S. new and advanced reactors, either bilaterally through U.S. government initiatives or multilaterally through the work of the IAEA, likely will require a considerable increase in resources from the United States and the IAEA. It is also likely that the IAEA will need considerable increase in its budget to meet the safety, security, and safeguards objectives for new or expanded nuclear programs.

Findings and Recommendations

Finding 9-5: The U.S. government has established a robust set of programs and organizations that will support advanced reactor developers across the spectrum of research, development, and deployment, including support for domestic and international safeguards and security research, international engagement, and licensing assessment. In addition, the United States and the International Atomic Energy Agency have initiated complementary programs to support the long-term effort needed to develop effective nuclear frameworks for the deployment of new and advanced reactors.

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[30] TWG-SMR includes the following Member States: Argentina, Australia, Canada, China, Finland, France, India, Indonesia, Iran, Italy, Japan, Jordan, Kenia, Republic of Korea, Pakistan, Russian Federation, Saudi Arabia, South Africa, Ukraine, United Kingdom, United States. See IAEA (2019).

Recommendation 9-5: The United States should develop a plan for increased and sustained long-term financial and technical support for capacity building in partner countries, including cost requirements for using U.S. national laboratories and universities as training platforms. This plan should include partnering with U.S. reactor vendors to develop a safety, safeguards, and security "package," where the United States and the vendor could offer customized support to a host country for developing and implementing new safety, safeguards, and security arrangements.

REFERENCES

Boyer, B.D., D.H. Beddingfield, P. Durst, and R. Bean. 2010. *Pebble Bed Modular Reactor Safeguards: Developing New Approaches and Implementing Safeguards by Design*. No. LA-UR-10-01760; LA-UR-10-1760. Los Alamos National Lab. (LANL), Los Alamos, NM (United States).

Cheng, L. 2021. *White Papers on Proliferation Resistance and Physical Protection: Characteristics of the Six GEN IV Nuclear Energy Systems*. BNL-222075-2021-COPR. Submitted to the White Papers on Proliferation Resistance and Physical Protection Characteristics of the Six GEN IV Nuclear Energy Systems Conference. https://www.osti.gov/servlets/purl/1818921.

Cipiti, B. 2021. "Advanced Reactor Deployment: Safeguards and Security Challenges." Presented to the Committee. October 4. https://www.nationalacademies.org/event/10-04-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-8#sectionEventMaterials. Available by request through PARO@nas.edu.

Cipiti, B. 2022. *Advanced Reactor Safeguards: 2022 Program Roadmap*. SAND2022-11143R. Sandia National Laboratories. https://doi.org/10.2172/1884929.

Croce, M., K. Koehler, K. De Castro, D. Mercer, S. Weidenbenner, M. Carpenter, D. Vo, D. Henzlova, and H. Menlove. 2020. *Experimental Validation of Nondestructive Assay Capabilities for MSR Safeguards*. https://gain.inl.gov/SiteAssets/2021-April_SafeguardsAndSecurityWorkshop/Reading/Experimental%20Validation%20of%20NDA%20for%20MSR%20Safeguards%20FY20%20Report.pdf.

DOE. 2023. DOE O 151.1D Chg1 (MinChg), Comprehensive Emergency Management System. https://www.directives.doe.gov/directives-documents/100-series/0151.1-BOrder-d-chg1-minchg

DOE-NE (Office of Nuclear Energy). 2021. "U.S. Department of Energy Seeks Input on Creation of HALEU Availability Program." https://www.energy.gov/ne/articles/us-department-energy-seeks-input-creation-haleu-availability-program.

DOE-NNSA (National Nuclear Security Administration). 2017 "Safeguards by Design guidance documents." https://www.energy.gov/nnsa/downloads/safeguards-design-guidance-documents.

DOE-NNSA. 2022. "Advanced Reactor International Safeguards Engagement Program." https://uploads.mwp.mprod.getusinfo.com/uploads/sites/54/2022/05/ARISE-Fact-Sheet_PA-Cleared_04152022.pdf.

Duguay, R. 2020. "Small Modular Reactors and Advanced Reactor Security: Regulatory Perspectives on Integrating Physical and Cyber Security by Design to Protect Against Malicious Acts and Evolving Threats." *International Journal of Nuclear Security* 7(1):Article 2. https://doi.org/10.7290/ijns070102.

Evans, A., J. Parks, S. Horowitz, L. Gilbert, and R. Whalen. 2021a. "U.S. Domestic Small Modular Reactor Security by Design." SAND2021-0768. Albuquerque, NM and Livermore, CA: Sandia National Laboratories. https://doi.org/10.2172/1665935.

Evans, A., S. Horowitz, R. Whalen, L. Gilbert, and R. Knudsen. 2021b. "DOE ARS—SMR Security by Design and Analysis." SAND2021-3956 C. Albuquerque, NM: Sandia National Laboratories. https://doi.org/10.2172/1861969.

Garrett, A.G., S.L. Garrett, R.J. Marek, M.R. Mitchell, C.R. Orton, R.T. Otto, T. Sobolev, and D.C. Springfels. 2021. *Advanced Reactor Safeguards: Lessons from the IAEA Safeguards Domain*. PNNL-31977. Richland, WA: Pacific Northwest National Laboratory. https://gain.inl.gov/SiteAssets/AdvancedReactorSafeguards/KeyThrustArea5/PNNL-31977_ARS_IAEA_Interfaces.pdf.

Government Accountability Office (GAO). 2019. *Nuclear Security: The International Atomic Energy Agency Could Improve Priority Setting, Performance Measures, and Funding Stabilization*. GAO-19-429. Washington, DC: Government Accountability Office.

Holcomb. D.E., R.A. Kisner, and S.M. Cetiner. 2018. *Instrumentation Framework for Molten Salt Reactors*. ORNL-TM/2018-868. https://info.ornl.gov/sites/publications/Files/Pub111607.pdf.

Hoyt N. and C. Moore. 2021. "Flow Enhanced Electrochemical Sensors for Molten Salt Reactors. Argonne National Laboratory." Presentation. https://gain.inl.gov/SiteAssets/2021-April_SafeguardsAndSecurityWorkshop/Presentations/Safe_Secure_Day3_Website/04-Flow%20Enhanced%20Electrochemical%20Sensors%20for%20MSRs-Hoyt.pdf.

IAEA (International Atomic Energy Agency). 2002. "IAEA Safeguards Glossary: 2001 Edition." 3. International Nuclear Verification Series. Vienna: International Atomic Energy Agency. https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf.

IAEA. 2010. *The Interface Between Safety and Security at Nuclear Power Plants*. INSAG-24. A Report by the International Nuclear Safety Group (INAG). Vienna: International Atomic Energy Agency.

IAEA. 2014. *Use of a Graded Approach in the Application of the Management System Requirements for Facilities and Activities*. IAEA-TECDOC-1740. Vienna: International Atomic Energy Agency.

IAEA. 2015. *Security of Nuclear Material in Transport*. Report No. 26-G. IAEA Nuclear Security Series. Vienna: International Atomic Energy Agency.

IAEA. 2016. "Basics of IAEA Safeguards." https://www.iaea.org/topics/basics-of-iaea-safeguards.

IAEA. 2020. *IAEA Nuclear Security Glossary: Terminology Used in IAEA Nuclear Security Guidance*. Draft. https://www.iaea.org/sites/default/files/21/06/nuclear_security_glossary_august_2020.pdf.

IAEA. 2022a. *Webinar on Safety, Security and Safeguards Interfaces and Challenges for Novel Advanced Reactors*. IAEA. February 3. https://www.iaea.org/resources/webinar/webinar-on-safety-security-and-safeguards-interfaces-and-challenges-for-novel-advanced-reactors.

IAEA. 2022b. *The Agency's Budget Update for 2023*. GC(66)/6. Vienna, Austria: International Atomic Energy Agency.

Iturria, F.P., and W. Li. 2022. "Time to Act: Integrating Safety, Security and Safeguards in the Design of Innovative Reactors." *International Atomic Energy Agency News*, July12. https://www.iaea.org/newscenter/news/time-to-act-integrating-safety-security-and-safeguards-in-the-design-of-innovative-reactors.

Kallenborn, Z. and P.C. Bleek. 2018. "Swarming Destruction: Drone Swarms and Chemical, Biological, Radiological, and Nuclear Weapons." *The Nonproliferation Review* 25(5–6):523–543.

Kovacic, D., P. Gibbs, and L. Scott. 2020. *Model MC&A Plan for Pebble Bed Reactors*. ORNL/SPR-2019/1329. Oak Ridge, TN: Oak Ridge National Laboratory.

Lauren-Kovitz, K. 2021. "Advanced Nuclear Security, Waste and Energy R&D (ANSWER), Progress and Promise." Presentation to the Committee. https://www.nationalacademies.org/event/10-04-2021/docs/D52630E2987C93A70C05AFBCF7DC862DC356D741B985.

Lines A.M., H.M. Felmy, A.S. Medina, S.D. Branch, and S.A. Bryan. 2020. *Evaluation of Optical Techniques for Molten Salt Reactor Material Control and Accounting*. PNNL-30360. Pacific Northwest National Laboratory. https://gain.inl.gov/SiteAssets/2021-April_SafeguardsAndSecurityWorkshop/Reading/Evaluation%20of%20Optical%20Techniques%20for%20Molten%20Salt%20Reactor%20Materials%20Control%20and%20Accounting%20-%20PNNL.pdf.

Liou, J. 2022a. "IAEA Director General Calls for Restraint, Reiterates Need to Ensure Safety of Ukraine's Nuclear Facilities and Their Staff." *International Atomic Energy Agency*, March 2. https://www.iaea.org/newscenter/news/iaea-director-general-calls-for-restraint-reiterates-need-to-ensure-safety-of-ukraines-nuclear-facilities-and-their-staff.

Liou, J. 2022b. "IAEA Initiative Sets Ambitious Goals to Support the Safe and Secure Deployment of SMRs." *International Atomic Energy Agency News*, July 4.

Maceda, M.G., E. Krabill, and W. Wan. 2022. "Incorporating New Technologies: Lessons from "Special Circumstances," Presentation, First International Nuclear Law Conference, Plenary Session No. 4, Safeguards: Issues and Trends, IAEA, April 27.

Martin, K. 1987. "Safeguards concept for the THTR-300 Thorium High Temperature Reactor." Pp. 147 in *Nuclear Safeguards Technology 1986: Proceedings of an International Symposium on Nuclear Material Safeguards*. Vol. 2. Vienna: International Atomic Energy Agency.

National Research Council. 2013. *Improving the Assessment of the Proliferation Risk of Nuclear Fuel Cycles*. Washington, DC: The National Academies Press. https://doi.org/10.17226/18335.

NEI (Nuclear Energy Institute). 2010. *Cyber Security Plan for Nuclear Power Reactors.* NEI 08-09 [Rev. 6]. Washington, DC: Nuclear Energy Institute.

NEI. 2016. "Cyber Security for Nuclear Power Plants." https://www.nei.org/resources/reports-briefs/cybersecurity-for-nuclear-power-plants.

NRC (U.S. Nuclear Regulatory Commission). 2010. *Nuclear Regulatory Guide 5.71: Cyber Security Programs for Nuclear Facilities*. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML0903/ML090340159.pdf.

NRC. 2018. "Options and Recommendations for Physical Security for Advanced Reactors." SECY-18-0076. https://www.nrc.gov/docs/ML1817/ML18170A051.html.

NRC. 2022. "Alternative Physical Security Requirements for Advanced Reactors." Proposed Rule, Docket No. NRC-2017-0227. https://www.regulations.gov/docket/NRC-2017-0227/unified-agenda.

NRC. 2022. "NRC, Proposed Rule: Alternative Physical Security Requirements for Advanced Reactors." SECY-22-0072. https://www.nrc.gov/docs/ML2133/ML21334A003.html.

Office of the Director of National Intelligence. 2022. *Annual Threat Assessment of the U.S. Intelligence Community*. Office of the Director of National Intelligence. https://www.dni.gov/files/ODNI/documents/assessments/ATA-2022-Unclassified-Report.pdf.

Prasad, S., A. Abdulla, M.G. Morgan, and I. Azevedo. 2015. Nonproliferation improvements and challenges presented by small modular reactors. *Progress in Nuclear Energy* 80:102–109.

Sanders, K.E., R.B. Pope, Y.Y. Liu, and J.M. Shuler. 2015. Interfaces among Safety, Security, and Safeguards (3S)—Conflicts and Synergies. INMM 56th Annual Meeting, July 12–16.

Snell, M.K., C.D. Jaeger, C. Scharmer, S.E. Jordan, K. Tanuma, K. Ochiai, et al. 2013. *Security by Design Handbook*. SAND2012-0038. https://doi.org/10.2172/1088049.

Suzuki, M., Y. Izumi, T. Kimoto, Y. Naoi, T. Inoue, B. Hoffheins. 2010. *Investigating 3S Synergies to Support Infrastructure Development and Risk-Informed Methodologies for 3S by Design*. IAEA-CN-184/64.

Transportation Emergency Preparedness Program. 2023. "Home." https://teppinfo.com.

10

Nuclear Exports and International Competition

Although U.S. reactor vendors are currently focused on successful completion of demonstration projects in the United States, many have plans to market their reactors internationally and may depend on significant international sales to justify the establishment of a manufacturing infrastructure. Expectations are that increased demand for new reactors will come from both existing and emerging nuclear power countries in Africa, the Middle East, and Asia, a development of importance in global efforts to address climate change (Ford and Abdulla 2021; IAEA 2021). When advanced reactor deployments expand to address these worldwide energy needs, those Nations who emerge as dominant in these markets will have opportunities to establish long-term interactions with host countries and will likely have influence in establishing norms that govern civilian nuclear safety, security, and safeguards in those countries. For example, in the past, U.S. prominence in the nuclear energy field made it a leader in safety, security, and nonproliferation efforts worldwide. More recently, however, other Nations have developed and expanded their nuclear energy sectors including the Russian Federation, South Korea, and China, while the U.S. nuclear sector has waned (Bowen 2022; IEA 2022).

Some have argued that the national security of the United States relies on regaining a leadership role in the future and worldwide expansion of nuclear energy (DOE 2020; Lovering et al 2020; Hamre 2013 and 2015). In addition, and as noted in Chapter 1, the U.S. Navy relies on nuclear-quality components and services provided by a robust commercial nuclear industry (Energy Futures Initiative 2017). However, a number of potential barriers exist for U.S. vendors in global markets, such as a complicated set of rules to market and sell nuclear products internationally, increased competition among nations, and potential expansion of nuclear reactors into newcomer countries that may lack effective government, industry, and societal frameworks to support the facilities. These potential barriers (some of which U.S. vendors have little control over) include development of regulatory oversight capabilities, financing mechanisms that provide market advantages to non-U.S. vendors, management of the fuel cycle, expanded transportation networks for nuclear materials, and education and outreach to local communities that may house reactors.[1] This chapter provides background on these topics and identifies opportunities and barriers to U.S. vendor expansion into international markets.

In addition to international safeguards requirements discussed in the previous chapter, there are a series of U.S. laws, international agreements, and export control mechanisms designed to limit proliferation of nuclear weapon technologies that affect U.S. vendors' ability to sell their nuclear technology internationally. The U.S. requirements differ by country and export controls may change rapidly in response to geopolitical events, adding complexity, legal implications, and unforeseen barriers to international sales.

[1] The IAEA has initiated an effort in which the Energy Communities Alliance is also engaged (with support from DOE's Office of Environmental Management) on establishing global connections between local jurisdictions and cities considering expansion of or into the advanced reactor market, encouraging "interaction between less experienced and more experienced local communities and organizations, which would contribute to improving communication among authorities, regulatory bodies, and operators." See International Atomic Energy Agency, 2023, "Technical Meeting for Municipalities with Nuclear Facilities," https://www.iaea.org/events/evt2101964.

TABLE 10-1 International Governance Instruments for Civilian Nuclear Safeguards, Safety, and Security

Safeguards	
Nuclear Non-Proliferation Treaty[a]	Requires non-nuclear weapons State Parties to conclude a safeguards agreement with the IAEA
United Nations Security Council Resolution 1540[b]	Obliges all UN Member States to account for nuclear weapons related materials in production, use, storage, and transport.
Safety	
The Convention on Nuclear Safety[c]	
The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management[d]	
Security	
The Convention on the Physical Protection of Nuclear Material (CPPNM)	Establishes legal obligations for physical protection on nuclear material during international transport under the auspices of the IAEA
Amendment, A/CPPNM 2005[e]	Establishes broader legal obligations for physical protection on nuclear facilities and material under the auspices of the IAEA, not just during transport
	Review of implementation of the 2005 Amendment

[a] See https://www.un.org/disarmament/wmd/nuclear/npt.
[b] See https://www.un.org/disarmament/wmd/sc1540.
[c] See https://www.iaea.org/topics/nuclear-safety-conventions/convention-nuclear-safety.
[d] See https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste.
[e] See https://www.iaea.org/publications/documents/conventions/convention-physical-protection-nuclear-material-and-its-amendment.

Consideration of safety, security and safeguards during the design process outlined in Chapter 9 will not change the fact that vendors will also need to operate within existing global governance frameworks. As of 2022, international governance instruments for civilian nuclear safeguards, safety and security do not distinguish between existing and advanced nuclear reactor types (see Table 10-1).[2] Negotiating new or renegotiating existing international legal instruments, either binding or non-binding, typically takes many years of effort with no guarantee of successful conclusion. Opportunities for crafting new global governance instruments for advanced reactors could arise, from the work by the IAEA[3] or out of necessity in response to the Russian invasion of Ukraine (see Box 10-1).

Nuclear liability has its own set of international governance instruments including the Vienna Convention on Civil Liability for Nuclear Damage and the Protocol to amend it, the Joint Protocol Relating to the Application of the Vienna Convention,[4] the Convention on Third Party Liability in the

[2] SMRs may require a separate Code for Safety and Security based on the differences outlined in Chapter 2.
[3] See International Atomic Energy Agency, 2023, “Conference of the Parties to the Amendment to the Convention of the Physical Protection of Nuclear Material 2022,” https://www.iaea.org/events/acppnm2022.
[4] International Atomic Energy Agency, 2023, “Nuclear Liability Conventions,” https://www.iaea.org/topics/nuclear-liability-conventions.

Field of Nuclear Energy,[5] the Convention on Supplementary Compensation for Nuclear Damage.[6] (See also *Nuclear Liability and Post-Fukushima Developments* [McIntosh 2022].) Most countries with existing nuclear power facilities have already included the principles and norms of these instruments in their national legal regimes. In addition, the IAEA's International Expert Group on Nuclear Liability plays an important role in examining issues related to the application of the international nuclear liability instruments and exploring developments in the nuclear industry that may affect the liability regime. In 2022, the group began discussing liability issues for SMRs, such as adjusting liability limits and financial security of operators owing to potential reduced exposure risks from an incident of some SMRs. Notably, the liability conventions apply to existing nuclear research reactors, which like some SMR designs use smaller amounts of radioactive materials, suggesting that some SMRs will not create new issues for the nuclear liability regime. However, an increase in countries with nuclear power reactors will argue for more universal adherence to the existing international nuclear liability instruments to ensure an orderly settlement of disputes in case of a nuclear incident.

Nuclear Cooperation Agreements (NCAs) and nuclear export controls provide the legal and practical foundations for U.S. nuclear trade and other forms of bilateral and multilateral cooperation in the nuclear field (see Appendix E). The chapter begins with a review of the landscape of U.S. and global nuclear cooperation agreements (NCAs) and nuclear export controls and the implications for the development and deployment of new and advanced reactors. This chapter also discusses international competition within the advanced reactor market and the implications to safety, security, and safeguards goals/norms. The chapter ends with a discussion of several U.S. government and IAEA initiatives to address these issues before concluding with findings and recommendations.

BOX 10-1
Seven Pillars for Nuclear Security and Safety

At the time of this writing, the full impact of the February 2022 illicit invasion of Ukraine by the Russian Federation on the nuclear sector worldwide remains unknown, but it will be profound. The Russian attacks on Ukrainian civilian nuclear facilities have prompted discussions on minimum requirements for nuclear safety and security, resulting in the development of the "Seven Pillars for Nuclear Security and Safety." The prospect of deployment scenarios that would place new and advanced reactors in more locations with potentially higher risks for armed conflict suggests that the current debate on the security and safety of Ukrainian nuclear facilities certainly will influence the development of standards for safety and security of facilities globally.[a]

The assault and occupation of the Chernobyl and Zaporizhzhia nuclear power facilities prompted IAEA Director General Rafael Mariano Grossi to propose "seven pillars" for nuclear security and safety at the 2 March 2022 IAEA Board of Governors meeting (IAEA 2022b):

- The physical integrity of the facilities—whether it is the reactors, fuel ponds, or radioactive waste stores—must be maintained;
- All safety and security systems and equipment must be fully functional at all times;
- The operating staff must be able to fulfil their safety and security duties and have the capacity to make decisions free of undue pressure;
- There must be secure off-site power supply from the grid for all nuclear sites;

[5] The full name for the convention is "the Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, as amended by the Additional Protocol of 28 January 1964, by the Protocol of 16 November 1982, and by the Protocol of 12 February 2004, entered into force 1 January 2022" with an unofficial consolidated text is available at: https://www.oecd-nea.org/jcms/pl_24768/unofficial-consolidated-text-of-the-paris-convention-as-amended-by-the-2004-protocol-nea/nlc/doc-2017-5/final .

[6] International Atomic Energy Agency, 2023, "Convention on Supplementary Compensation for Nuclear Damage," https://www.iaea.org/topics/nuclear-liability-conventions/convention-supplementary-compensation-nuclear-damage#:~:text=The%20Convention%20on%20Supplementary%20Compensation,damage%20caused%20by%20a%20nuclear.

- There must be uninterrupted logistical supply chains and transportation to and from the sites;
- There must be effective on-site and off-site radiation monitoring systems and emergency preparedness and response measures; and
- There must be reliable communications with the regulator and others.

Director General Grossi indicated that the IAEA needed a commitment from all parties in the conflict to provide the technical assistance needed to ensure continued safe and secure operation of the facilities (IAEA 2022b). Later, Grossi and IAEA inspectors visited the plant and two inspectors have remained in place.[c]

[a] The Russian large-scale invasion of Ukraine in February 2022, even if it will not produce immediate change in the international instruments that govern nuclear technology, had at least one clear lesson for the nuclear community: nuclear facilities, from power facilities to research reactors, in war zones should not be subject to military attack. Article 56 of the 1977 Additional Protocol I and Article 15 of Additional Protocol II to the Geneva Conventions of 1949 had already prohibited making “works containing dangerous forces” (Article 56 specifically including “nuclear electrical generating stations”) an object of a military attack, with nearly 170 States as parties to the Protocols. There are proposals to strengthen the protections for nuclear facilities in war zones (see https://www.iaea.org/sites/default/files/22/09/ukraine-2ndsummaryreport_sept2022.pdf; https://www.defenseone.com/ideas/2022/03/what-we-learned-russias-assaults-nuclear-plants/363487/; and https://www.stimson.org/2022/nuclear-security-during-armed-conflict/).

[b] “In an appeal to the IAEA’s 173 Member States, Mr Grossi called on all countries to uphold international law and fulfill the obligation they agreed to when, in 2009, they unanimously reaffirmed the General Conference resolution stating that ‘any armed attack on and threat against nuclear facilities devoted to peaceful purposes constitutes a violation of the principles of the United Nations Charter, international law and the Statute of the Agency.’ ” (Liou 2022).

[c] See https://www.reuters.com/world/europe/two-iaea-inspectors-stay-zaporizhzhia-nuclear-plant-permanently-russian-envoy-2022-09-02.

NUCLEAR COOPERATION AGREEMENTS AND NUCLEAR EXPORT CONTROLS

The export of civilian nuclear reactors and nuclear technology between countries is allowed under the broad framework established by Nuclear Cooperation Agreements (NCAs). These agreements set the terms for future trade between two countries but do not guarantee that trade will take place.[7] In the Unites States, Section 123 of the Atomic Energy Act defines the U.S. process and requirements for negotiating NCAs (NCAs are therefore commonly known in the United States as “123 Agreements”). Currently, the United States has twenty-two 123 Agreements with 48 countries and the Taiwan Economic and Cultural Representative Office (TECRO); two additional NCAs are with EURATOM and the IAEA. The United States has yet to finalize or in some cases begin negotiations with many countries in regions that have seen increased interest in nuclear power, notably those in Africa, Central and Southeast Asia, and Latin America (see Figure 10-1). Efforts to expedite the establishment of NCAs with countries that are potential customers for U.S. vendors may be necessary. For additional information on NCAs, see Appendix E.

[7] For more details on the negotiation, timeline, and status of current 123 Agreements, see Appendix E.

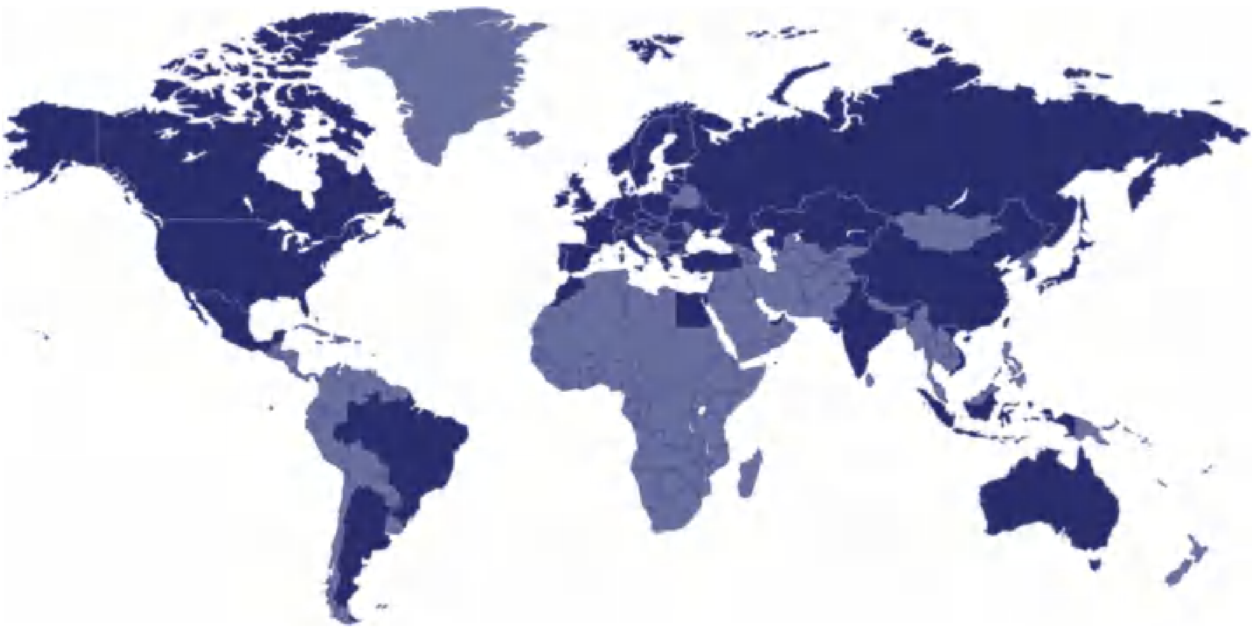

FIGURE 10-1 Countries with active 123 Agreements with the United States as of December 7, 2022.
NOTE: This map does not include the 123 Agreement between the United States and South Africa, which was set to expire in December 2022. In September 2022 this Agreement was extended through Presidential Determination No. 2022-21 (https://www.federalregister.gov/documents/2022/09/06/2022-19366/presidential-determination-on-the-proposed-agreement-to-extend-the-agreement-for-cooperation-between).
SOURCE: Committee generated, modified from Department of Energy, National Nuclear Security Administration, 2022, "123 Agreements for Peaceful Cooperation," https://www.energy.gov/nnsa/123-agreements-peaceful-cooperation.

Once an NCA has been established, national export control systems define the required authorizations, licenses, and legal conditions for export of specific nuclear items between the two countries (see Figure 10-2). Many countries coordinate their export controls through their participation in the Nuclear Suppliers Group (NSG).[8]

A new State Department diplomatic initiative aims to assist in the early development of strategic civil nuclear cooperation relationships, support U.S. civil nuclear industry and vendors, and advance U.S. national security and nonproliferation goals. Nuclear Cooperation Memoranda of Understanding (NCMOUs) provide a framework for developing cooperative relationships with the United States on civil nuclear issues. For example, NCMOUs can allow the United States to assist its potential future nuclear trading partners, especially newcomer countries, in building their nuclear infrastructure and lay the foundation for and develop future civilian nuclear cooperation, such as 123 Agreements or a Part 810 authorization (described below). NCMOUs do not permit exports and they do not replace 123 Agreements.[9]

[8] See: Nuclear Suppliers Group, 2022, "About the NSG," https://www.nuclearsuppliersgroup.org/en; Nuclear Suppliers Group, 2022; "What are the NSG Guidelines," https://www.nuclearsuppliersgroup.org/en/27-faq/198-what-are-the-nsg-guidelines#:~:text=The%20NSG%20Guidelines%20are%20sets%20of%20conditions%20of,to%20apply%20those%20Guidelines%20via%20their%20national%20legislation.

[9] U.S. Department of State, 2023, "Nuclear Cooperation Memoranda of Understanding (NCMOU): Fact Sheet," https://www.state.gov/nuclear-cooperation-memoranda-of-understanding-ncmou.

Since the passage of the Atomic Energy Act in 1946 and the beginning of the nuclear age, the United States has established controls on the transfer of nuclear information and technology related to civil nuclear power and reactors, as did other then-emerging nuclear suppliers (Hamblin 2021, Ch. 1; Daniels and Krige 2022 Ch. 3). Currently, the United States has three distinct yet interconnected processes for governing the export of civil nuclear items, one led by the Department of Energy (DOE), one led by the U.S. Nuclear Regulatory Commission (NRC), and one led by the Department of Commerce (see Figure 10-2 and Table 10-1).[10] These three agencies interact regularly when granting licenses or authorizations for nuclear or dual-use items that lay within their scope (see Table 10-2) which helps ensure that decisions are well-understood by all participating agencies and that the final decisions in one process are not at cross-purposes to another.

FIGURE 10-2 U.S. Nuclear Export Control Licensing Trident.
SOURCE: K. Strangis, 2021, "Overview of 10 CFR Part 810 Program," Slide 3, Presented at Laying the Foundation for New and Advanced Nuclear Reactors in the United States Meeting #8, October 5.

TABLE 10-2 Summary of U.S. Governance Instruments of Relevance to Advanced Reactors Export

Vehicle	Scope	Examples	U.S. Government Entities	Average Time
Nuclear Cooperation Agreements or 123 Agreements	defines terms of (future) trade	(see Figure 10-1)	DOS w/input from DOE, Commerce, DoD	400 days
10 CFR Part 810 authorizations	technical assistance	training, sharing of knowledge, expertise; training materials; blueprints or other physical documents or those in digital form including certain software	DOE w/concurrence from DOS, DoD, Commerce, NRC	270 days (9 months)
10 CFR Part 110.8(a) licenses	tangible nuclear items	nuclear equipment and materials, nuclear reactors and components of reactors, etc.	NRC w/input from DOE, Commerce, DoD	~months to more than a year[a]

[10] A fourth process, led by the Department of State, exists for nuclear items under the International Trafficking in Arms Regulations (ITAR) in 22 CFR 120-130. Notably, Category XV of the Munitions List in the ITAR includes space-based nuclear reactors, their associated power conversion systems, and nuclear thermal propulsion systems designated "developmental, experimental, research, or scientific, or having a commercial, civil, or military end-use."

Export Administration Regulations (EAR) licenses	dual-use items: goods, services, and technologies with primarily commercial but also with potential nuclear weapons proliferation applications	turbines, generators, switching gear, pipes, and valves; health and safety equipment (i.e., radiation detectors and monitors, fire safety, and facility safety); general infrastructure (i.e., telecommunications, tools and maintenance equipment); and materials and manufacturing equipment	Commerce consensus decision w/DOS, DOE, DoD	90 calendar days to resolve a license application (does not include prelicense checks or negotiations for government-to-government assurances)

[a] These values are rough estimates. See, for example, https://www.mondaq.com/unitedstates/export-controls-trade-investment-sanctions/1140062/nuclear-export-controls-a-brief-overview-of-nrc-and-doe-regulations.

DOE and Part 810

Under 10 CFR Part 810, the DOE Secretary is given the authority to authorize the export of nuclear technical assistance.[11] Two types of authorizations exist: Specific Authorizations determined on a case-by-case basis, and General Authorizations deemed “non-inimical” to the interests of the United States for exports to be sent to a list of ~50 countries that generally parallels countries with which the United States has 123 Agreements.[12] The DOE Secretary has the authority to issue Specific Authorizations[13] under Part 810 to share nuclear assistance with countries that do not have 123 Agreements with the United States, as demonstrated most recently in March of 2019 when then-Secretary Rick Perry approved Part 810 specific authorizations for exports by U.S. companies to Saudi Arabia (CRS 2019).

The DOE Part 810 licenses cover a broad range of activities, from sharing digital blueprints to directly assisting in technical training, including the release of related commercial proprietary information.[14] Some of these activities lay the groundwork for a commercial partnership or sale, so Part 810 authorizations often serve as a leading indicator for vendor interest in future NRC and Commerce licensing applications for export of physical nuclear items. DOE has already received Part 810 export authorization applications related to U.S. advanced reactor technology, both for transfers of technical information to potential customers and for “deemed” exports for foreign personnel exposure to such intangible technology inside the United States (Strangis 2021). Currently, the average time for Part 810 authorization, which is the essential first step in sales with other countries, is 9 months (down from 16 months in 2016 owing to implementation of process improvements by DOE). A swift Part 810 process is more important in capturing a sale than the other licensing processes, which can be concluded post-sale.

[11] Nuclear technical assistance is also referred to as “intangible nuclear technology” which can include blueprints or other physical documents or those in digital form, and includes training, sharing of knowledge, expertise, and certain software.

[12] For the list of generally authorized destinations, see 10 CFR Appendix A to Part 810, available at https://www.ecfr.gov/current/title-10/chapter-III/part-810/appendix-Appendix%20A%20to%20Part%20810, accessed July 3, 2022.

[13] Specific Authorizations to countries without a 123 Agreement with the United States require detailed analysis and review by other agencies (Strangis 2021, slides 5 and 8; and CRS 2019).

[14] The authorization does not allow retransfers of exports, unless authorized under license or an exemption.

NRC and Part 110

The NRC issues both individual and general licenses for exports of "nuclear reactors and especially designed or prepared equipment and components for nuclear reactors" under 10 CFR Part 110.8(a). The tangible nuclear items covered by Parts 110 (and 810) relate mainly to the items listed in Part 1 of the NSG Guidelines (equipment and materials[15]). General licenses, which are issued by force of the regulation and do not require an application, apply to reactor components to eligible countries and to small quantities or special forms to countries not embargoed.[16] The general license is available for exports to about 35 countries, but the license is not available for exports to most countries in Asia, Africa, or the Middle East.[17]

In August 2019, the NRC formed an interagency Advanced Reactor Export Working Group (AREWG) in anticipation of applications for export licenses for advanced reactors.[18] In a review of five reactor types and 14 designs the NRC believed most likely to be the basis for export license applications in the next decade, the AREWG concluded that the existing Part 110 process could license relevant materials and components with only some clarifications, such as the use of molten salt as a coolant.[19] The NRC, however, intends to continue to review the regulations and practices. Moreover, the AREWG's mandate did not specifically include a focus on safeguards or security concerns.[20] As with the Part 810 licenses, obtaining the required government-to-government nuclear assurances has a major impact on the length of the NRC export licensing process.

Commerce and Export Administration Regulations

Under the U.S. Export Administration Regulations (EAR), the Department of Commerce licenses the export of "dual-use" nuclear power related items such as goods, services, and technologies with primarily commercial but also with potential nuclear weapons proliferation applications. Generally, these items appear in the Commerce Control List (CCL)[21] and represent the "balance of plant" such as turbines, generators, switching gear, pipes, and valves; health and safety equipment such as radiation detectors and monitors, fire safety, and facility safety; general infrastructure such as telecommunications, tools, and maintenance equipment; and materials and manufacturing equipment (Clagett 2021, slide 2). Retransfers of U.S. origin dual-use items also have licensing requirements under the EAR.[22]

Many dual-use exports can go to destinations without the need for a license application. If the item is classified as "EAR99," it may be able to be shipped with a No License Required (NLR) designation. The EAR also outlines a range of license exceptions that allows exports of items on the CCL without a license. If a license it required, the EAR includes a requirement to resolve a license application within 90 calendar days. However, several important associated activities, such as conducting prelicense

[15] See Nuclear Suppliers Group, 2019, Guidelines for Nuclear Transfers, http://nuclearsuppliersgroup.org/images//2019NSG_Part_1.pdf.

[16] Found in Part 110.28 and Part 110.29 respectively.

[17] U.S. Nuclear Regulatory Commission Regulations, n.d., "Title 10, §110.26(b)" in *Code of Federal Regulations*, Washington, DC: Government Publishing Office and National Archives and Records Administration.

[18] See U.S. Nuclear Regulatory Commission, 2022, "U.S. Nuclear Regulatory Commission Preparations for the Export of Advanced Reactors," https://www.nrc.gov/about-nrc/ip/us-nrc-prep-export-advanced-reactors.html.

[19] See U.S. Nuclear Regulatory Commission, 2022, "U.S. Nuclear Regulatory Commission Preparations for the Export of Advanced Reactors," https://www.nrc.gov/about-nrc/ip/us-nrc-prep-export-advanced-reactors.html.

[20] U.S. Nuclear Regulatory Commission, 2022, "U.S. Nuclear Regulatory Commission Preparations for the Export of Advanced Reactors," https://www.nrc.gov/about-nrc/ip/export-import/us-nrc-prep-export-advanced-reactors.html.

[21] Bureau of Industry and Security, 2020, "Commerce Control List (CCL)," https://www.bis.doc.gov/index.php/regulations/commerce-control-list-ccl.

[22] A retransfer refers to an item that is exported (transferred) to a foreign end-user who subsequently transfers those items to another end-user in the host country or to an end-user in a third country.

checks, required consultations with other governments under bilateral or multilateral arrangements, or obtaining government-to-government assurances, are excluded from the 90-day limit.[23] As with the two other licensing systems, the EAR does not distinguish between non-light water or "advanced" reactors and more common light-water reactors. Although a Commerce Department official noted that the United States is discussing items that might be unique to advanced reactors or related items not currently subject to controls on dual-use items, they see existing U.S. export controls as capable of successfully processing applications for the export of items related to new and advanced reactors (NRCRIC 2021).[24]

Interagency Coordination

Although each of the agencies listed above have distinct licensing scope, formal and informal links exist among them. The Department of State coordinates the views of the Departments of Commerce, Defense, and Energy on obtaining assurances subject to the associated 123 Agreement and that license criteria have been met. For Part 810 authorizations, DOE needs concurrence from the Department of State along with conducting consultations with the Departments of Commerce and Defense and the NRC. Similarly, upon receipt of a license application, Commerce must share the application with the Departments of Defense, Energy, and State (and, as appropriate, other bodies) for a consensus decision. For Part 110 licenses, for example, the NRC needs to obtain a view from executive branch agencies. With the 90-day limit for issuing a licensing decision from Commerce, the EAR includes an often-used process for resolving interagency differences. More informally, those working on these licenses speak and work regularly with one another.

Even when coordinated and working simultaneously across the authorizations and license required, the average times noted in Table 10-2 suggest that the export control process takes about two years at a minimum. These average process times are for current technology exports, where the regulators have considerable experience. For licensing new or first-of-a-kind items, regulators will need additional time to gain familiarity with the relevant technologies and associated processes. Similarly, licensing to new national markets and new end-users in Africa, Asia, and the Middle East will require additional time for regulators to evaluate the risk and make their determinations.

U.S. government officials perceive the biggest challenge for U.S. export controls of new and advanced reactors as stemming from the lack of awareness of vendors of the Part 810 and EAR licensing requirements and processes (Habighorst 2019; NRCRIC 2019). Vendors, for example, often do not seem aware of the breadth of the Commerce controls, which include, for example, vendor collaborations with universities or exporting of testing equipment. Nor are they prepared for the international political complexities and the associated licensing criteria, such as the challenges in obtaining government-to-government assurances with new partner countries for new end-users. DOE, the NRC, and the Department of Commerce have done outreach individually and collectively, including interagency teams presenting to broad audiences and conducting in-house training. Although the pandemic has made on-line outreach less effective than face-to-face interactions, an apparent lack of proactive efforts by the vendor community to work directly with the licensing agencies greatly compounds the issue (NRCRIC 2019). Nonetheless, officials believe that U.S. export control licensing processes itself does not need to hamper U.S. competitiveness. However, the lead U.S. agencies have not made a coordinated outreach effort specifically designed for U.S. vendors for new and advanced reactors. For example, outreach conducted

[23] See Code of Federal Regulations, "Title 15 CFR Part 750," https://www.ecfr.gov/current/title-15/subtitle-B/chapter-VII/subchapter-C/part-750.

[24] See U.S. Nuclear Regulatory Commission, 2021, "M3 U.S. Regulatory Preparations for the Export of Advanced Reactors," https://www.nrc.gov/public-involve/conference-symposia/ric/past/2021/docs/abstracts/sessionabstract-3.html. For the transcript of the session, see https://www.nrc.gov/docs/ML2122/ML21225A692.pdf.

by the Bureau of Industry and Security in 2021 did not appear to include any special focus or events on new and advanced reactors.[25]

Findings and Recommendations

Finding 10-1: 123 Agreements provide a foundation for the eventual transfer of nuclear items from the United States to existing and emerging nuclear-capable countries. Negotiations typically take years and require the application of significant diplomatic resources. Once a 123 Agreement has entered into force, three main U.S. export control processes are used to authorize or license nuclear exports: Part 810 (Department of Energy), Part 110 (Nuclear Regulatory Commission), and Export Administration Regulations (Department of Commerce). Each licensing or authorization process adds additional time, from as little as 90 days to more than 9 months. Therefore, obtaining U.S. export licenses—from negotiation of a 123 Agreement through exchanges of design information (Part 810) to reactor construction—may take at least several years for the first nuclear export to a country, particularly for a first-of-a-kind reactor plant design.

Finding 10-2: The U.S. federal agencies—Department of Energy, Nuclear Regulatory Commission, and Department of Commerce—working on the different licensing and authorization processes regularly speak and work with one another when presented with an application. This close coordination across these lead agencies has several benefits: it may reduce the need for extensive modification to manage the export of new and advanced reactors and their technologies, and, given that the export of any individual advanced reactor by a U.S. vendor would likely involve all three licensing processes, this interaction across the agencies plays an important role in ensuring that decisions in one process do not work at cross-purposes with the two other licensing processes. There is little evidence, however, that these agencies have offered coordinated and targeted outreach efforts to U.S. vendors of new and advanced reactors.

Recommendation 10-1: Efforts should be made to shorten the timelines for putting in place 123 Agreements and review of export applications. The three lead export control agencies should increase efforts to educate U.S. nuclear vendors on the requirements, bureaucratic resources, and timelines associated with U.S. 123 Agreements and U.S. nuclear export controls. These efforts would include the creation of new specialized guidance materials, training activities, and other forms of technical assistance, especially for new vendors and in coordination with Gateway for Accelerated Innovation in Nuclear and similar initiatives, in anticipation of new license applications.

INTERNATIONAL MARKETS AND COMPETITION

The majority of present-day nuclear reactor deployments occurs in countries with well-established regulatory processes and the capability for addressing safety, security, and safeguards risks. This status quo is rapidly changing, however, due largely to two synergistic market factors. In the coming decades, the majority of increased energy demand is projected to occur in developing and nuclear newcomer countries (Ford and Abdulla 2021). On the supply side, many advanced reactor vendors are seeking to develop lower cost, mass-manufacturable nuclear reactors that would be affordable to more

[25] See U.S. Department of Commerce, 2021, "Annual Report to Congress," https://www.bis.doc.gov/index.php/documents/pdfs/3140-annual-report-of-the-bureau-of-industry-and-security-for-fiscal-year-2021/file, pp. 31–32. See also Bureau of Industry and Security, 2020, "FY 2023 BIS Seminar Schedule," https://www.bis.doc.gov/index.php/compliance-a-training/current-seminar-schedule.

countries. Increasing the worldwide deployment of advanced nuclear reactors will require reinvestigating—and in some cases reimagining—global protocols for nuclear regulatory processes for limiting safety, security, and safeguards risks. The specific implications of this growth, however, depend heavily on both the number of new nuclear reactors and institutional readiness of the countries where they are being built. Growth scenarios for global nuclear energy use, projected from 2020 to 2050, range from nearly stable nuclear use to more than double (IEA 2022a; IAEA 2021).

For much of the early history of nuclear energy development, the United States was at the forefront of civilian nuclear deployment. For example, one-third of the 637 reactors listed in the IAEA's worldwide Power Reactor Information System (PRIS) database (operational + shutdown) were either built by a U.S.–based developer or in partnership with a U.S. developer.[26] This leadership position in both design and deployment has declined dramatically since the early 1980s for reasons that vary from a general lack of a sustainable order book, to a perception that a U.S. or other western development company will be more expensive that competing options from Russia or China, and that the regulatory burden of dealing with western developers is too high (MIT 2003). As a result, while a few international reactors currently being deployed have their origins in U.S. companies, only ten of the 55 reactors (~ 4 percent) are being built using U.S. designs—two in the United States and eight reactors in China (i.e., Westinghouse's AP1000s). This decrease of U.S. participation in the global nuclear development market is in stark contrast to the continued, aggressive marketing from competitor nations such as Russia and ongoing large-scale reactor development by China (albeit currently dominated by internal deployments) (IEA 2022b; Bowen and Dabbar 2022).

As a competitor in the international nuclear marketplace, Russia has stood out for several reasons. Prior to Russia's invasion of the Ukraine in February 2022, Russia dominated the international market with 17 units under construction in seven countries (Schneider and Froggatt 2022, p. 16). In addition, of 509 signed NCAs and 228 less formal memoranda of understandings and policy statements (post-2000), Russia has three times more agreements to supply tangible nuclear technology (physical nuclear items), such as NPPs, than the next suppliers (France and the United States) and more than twice the number of countries than the next supplier (France) (Jewell et al. 2019).[27] Russia also has had at least two dozen entities working on advanced reactors, including molten salt reactor, liquid metal-cooled fast reactor, HTGR, and SMR designs, and offers other new power reactor options, such as floating NPPs (Allen and Milko 2017; World Nuclear News 2021). The Russian success in marketing arises in part from its willingness to provide very favorable financial terms, thereby advancing a foreign policy objective of having an important role in the customer country's critical energy infrastructure for the life of the plant (as long as 100 years). In pursuit of this objective, it also offers favorable terms on fuel supply and even the take-back of spent fuel, alleviating the customer country's obligation to develop disposal capability.[28]

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[26] Of the total, 202 (32 percent) were U.S. developed or in partnership with U.S. developers. See International Atomic Energy Agency Power Reactor Information System Database, 2022, https://pris.iaea.org/PRISTA/frmChooseReport.aspx?Menu=STANDARD+REPORTS.

[27] However, the United States has the most agreements or other arrangements when it comes to intangible nuclear technology cooperation, especially in the areas of safety and security. See J. Jewell, M. Vetier, and D.G. Cabrera, 2019, "The International Technological Nuclear Cooperation Landscape: A New Dataset and Network Analysis," *Energy Policy* 128:838–852, https://pure.iiasa.ac.at/id/eprint/15756/1/IR_nuclear_draft_180712.pdf.

[28] Reformers have suggested that Russia has less stringent conditions in its NCAs—arguably making Russian-based reactors more competitive options (Stulberg and Dorsey 2020, p. 94 plus footnotes). While this appears to have been true in the past, a recent examination of the quality of 109 U.S. and Russian NCAs from 1990 to 2020 on safeguards requirements, transfer restrictions, limits on enrichment, limits on reprocessing of spent fuel, and controls on retransfers found that Russian agreements have tightened significantly over time, especially after the consolidation of the Russian nuclear industry within state-owned Rosatom in 2007, equaling in quality to U.S. 123 Agreements since around 2017 (Stulberg and Darsey 2020). Examining a subset of agreements between Russia and nuclear newcomers shows a similar pattern with less than a 5 percent difference in the quality scores since 2018 (Stulberg and Darsey 2020).

Of course, recent events in Ukraine and the resulting sanctions will certainly impact the recent dominance of Russia in the existing nuclear reactor market overall, although it might not have much effect on potential high-growth markets in Africa, the Middle East, and Southeast Asia. The recent Russian willingness to use the curtailment of natural gas to exert pressure on Western Europe could offer an opening for western developers in markets where dependence on Russia for energy needs including oil, gas, and nuclear will now be seen as a much higher risk proposition than was previously the case. These actions by Russia may also open doors to international cooperation among the G7 Nations to displace Russia's commercial dominance (Ichord 2022).

Less information on Chinese NCAs exists, but their role in international nuclear cooperation activities continues to expand (Jewell et al. 2019). China not only has the most expansive current plans for domestic nuclear power reactor construction, but it has also made civil nuclear cooperation an integral part of its Belt & Road Initiative (Lin et al. 2020). According to one study, at least 25 countries participate in nuclear reactor cooperation under the Initiative, including HTGR projects with Indonesia, Saudi Arabia, South Africa, and the UAE and a Pebble Module SMR project with Jordan (Lin et al. 2020). In addition, at least 11 Chinese entities have been working on designs for molten salt reactors, liquid metal-cooled fast reactors, Pebble Bed Reactors, SMRs, Supercritical Water-cooled Reactors, and Supercritical CO2 Reactors (Allen and Milko 2017). Despite the aim of the Belt & Road Initiative to cooperate with countries without regard to their economic or government systems, this expansion has the potential to lead to less stringent NCAs, especially with nuclear newcomers. Although this is a potential risk, some analysts note that China has taken steps in recent years to increase its commitment to nuclear safety and to strengthen its controls on nuclear transfers, such as through its new export control law (State Council Information Office of China 2019).

As noted earlier, the United States and European countries were historically the dominant force in new nuclear development but now Russia and China are playing a leading role in international nuclear development and deployment. In some cases, development and construction support are coupled with extraordinarily favorable financial terms, long-term operating contracts and fuel return, easing the necessity for a host nation to develop robust indigenous capacity to manage the technology in the near-term and creating a long-term geopolitical tie (World Nuclear News 2016). The challenge for the United States and OECD vendors is in not only developing the technologies that hold appeal in foreign markets but also developing a more holistic approach for vendor support before State-sponsored vendors have created even more challenging barriers to entry in the emerging markets for nuclear power. The diminution of U.S. and OECD vendors in the markets has decadal impacts for safety, security, and safeguards. As scholars have noted recently:

> [In the] context of the growing tensions and confrontation among the major powers, the race is on to commercialize the new generation of SMRs and MNRs for civilian and military use. The United States and its European and Asian allies need to progress rapidly beyond research, development, and demonstration efforts into effective manufacturing, financing, and implementation strategies to lead this global effort and successfully confront the emerging competition from China and Russia. (Ichord 2022 [webpage])

and

> Without the United States and other countries with strong accountability and governance as viable competitors, nuclear safety and security norms, standards, practices, and enforcement would likely become precarious or a secondary consideration. (Nakano 2020, p. 2)

Finding

Finding 10-3: As some growth scenarios indicate, there could be a significant increase in the number of deployed advanced reactors throughout the world by 2050. Because no single country (or no single vendor within a country) is likely to be able to support the entire international marketplace, all competitors and competitor nations should recognize that they have shared responsibility in minimizing safety, security, and safeguards risks.

National Security and International Markets

This changing landscape in international leadership in nuclear development reflects a potential shift in national security influence. Because the United States still has a major role in the application of nuclear power owing to the composition of the current international fleet of reactors, and its position as a nuclear weapons state, it retains significant influence on the worldwide system for safety, security, and safeguards. Some have voiced concern that U.S. influence will wane if the United States does not pursue nuclear power at home and is not a major participant in the international market (Hamre 2015; Ichord and Oosterveld 2019; Kerr et al. 2014). There is little doubt that U.S. influence as a provider of choice for this technology continues to decrease. As more nations consider the use of nuclear power and as U.S. nuclear developers seek to take advantage of these new market opportunities, there is a critical question that the United States and western developers and governments must address if they are to regain their status as developers of choice for nuclear technology: *Will the long-term interactions established through nuclear facility deployments/agreements by Russia and China to different countries—including newcomer countries—lead to long-term influences on the countries in which the reactors are deployed? And how can the United States and its allies ensure a long-term commitment to safety, security, and safeguards (especially in light of the Russian invasion of the Ukraine)?*

The answers to these questions likely center on two key factors: (1) reexamining the role of international partnerships; and (2) developing enhanced financing and government support options. The latter is most critical when considering the potential future vast need for sources of clean energy.

Partnerships

Partnerships may help streamline key support activities such as fuel supply and waste remediation while ensuring quality, safety standards, security, and safeguards controls. The Gen IV International Forum (GIF), for example, originated in 2000 to discuss international collaboration for the development of nuclear energy systems using fourth generation nuclear reactors. The GIF currently has 11 active member countries (plus EURATOM), a Senior Industry Advisory Panel, and five "external collaborators, i.e., the OECD Nuclear Energy Agency, the IAEA, the Multinational Design Evaluation Program, the World Nuclear Association, and the International Framework for Nuclear Energy Cooperation IFNEC). Among the external collaborators, the IFNEC similarly focuses on new nuclear energy initiatives focuses on new nuclear energy initiatives, aiming to ensure that new nuclear energy initiatives meet the highest standards of safety, security, and safeguards.[29] The group currently includes 33 nations and 31 observer countries, and three working groups.[30]

While this type of interaction is potentially valuable in developing customer/client relationships, it is unclear whether these partnerships will provide a vehicle for enhanced partnering that may improve efforts by western nations to compete effectively. Some of the efforts have not born much fruit. The GIF Proliferation Resistance and Physical Protection assessment methodology Working Group, for example, last published a revised version of its methodology in 2011 (although it added a bibliography relevant to its methodology in 2022), the same year it last reported on the proliferation resistance and physical protection of the six Gen IV nuclear energy systems identified by the GIF. Similarly, U.S. government support for IFNEC has fluctuated and it is not apparent that it has led to new openings for western developers with potential customer nations.

Other collaborative efforts could be focused on likely pathways for partnerships between U.S. allied nations and include shared facilities and expertise to expedite advanced reactor demonstrations (Bowen 2020).

Financing Options

To improve competition, the United States and western nations could examine additional financing structures than currently exist that will help developers compete with state-supported competitors such as China or Russia.

Most of the expected growth in electricity demand over the next several decades is expected to occur in non-OECD nations (Kahan 2020). In many cases, these nations do not have the financial resources and access to credit that allows them to independently support large-scale energy development projects required to meet the growing demand (Ford and Abdulla 2021).[31] Most will require support from vendors and vendor nations in the form of low-cost export credit financing. This financing challenge significantly affects U.S. nuclear vendors because, in many cases, their foreign competitors (e.g., Russia and China) are backed by their own governments, which offer financing independent of issues such as customer nation credit worthiness (NEI 2022).

U.S. private companies must compete in this, at times, unbalanced global marketplace to win reactor plant orders. However, the U.S. government has several financial tools to support and expand the commercial technology export sector. These could include loan guarantees, and as export financing. Because resulting civil nuclear partnerships can lead to other forms of bilateral economic cooperation, it would be prudent to consider the use of these tools to counterbalance foreign government sponsorship and keep the U.S. competitive.

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[29] For more information on the IFNEC, see https://www.ifnec.org/ifnec. The U.S. Global Nuclear Energy Partnerships (GNEP), formed in 2006, identified key areas that should be evaluated for international teaming. Ultimately, GNEP was rebranded and transitioned into IFNEC in 2010. See also CORDEL, https://world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/REPORT_Facilitating_Intl_Licensing_of_SMRs.pdf. (The CORDEL Working Group established the Small Modular Reactor Ad-Hoc Group [SMRAG] in 2013 to elaborate a path toward harmonized and well-regulated global SMR deployment.)

[30] (1) *The Reliable Nuclear Fuel Services Working Group (RNFSWG)*, which addresses nuclear fuel leasing and other considerations around comprehensive nuclear fuel supply goals, and included evaluation of back-end fuel cycle options. (2) *The Infrastructure Development Working Group (IDWG)*, which addressed human resource development, radioactive waste management, small modular reactors, financing options, engagement with specialist organizations and identified infrastructure requirements for an international nuclear fuel services framework that may enable nuclear power deployment in many countries. (3) *The Nuclear Supplier and Customer Countries Engagement Group*, which focuses on nuclear safety, project development (supply chain issues in particular) and financing as well as public acceptance and accountability.

[31] The use of “large-scale” acknowledges that for some nations even a small number of SMRs would be a large-scale energy development effort when considering grid scales and capacity of their institutions.

Financing of nuclear projects in foreign countries has taken many forms, including the following (see Chapter 3 and IAEA 2018):

Government Financing Options

Direct Government Financing: In this form of project financing, the government serves as the sole funding agency for a nuclear development project. For example, the Chinese government funds the Qinshan 1 and 2 projects.

Loan Guarantees: This is a more traditional form of international nuclear development financing, especially in government managed or tightly regulated energy markets. The U.S. government offers loan guarantees that may provide support for domestic advanced reactor development through the DOE Loan Programs Office, but not for overseas projects.

Government-to-Government Loan: In this mode of financing, the lending government usually has a stake in a state-run NPP vendor, so this financing method provides a market for its plants. In many cases, the goals of government-to-government financing include a geopolitical component and may lead to very favorable repayment terms. This type of financing is provided by China to Pakistan and offered by Russia to multiple countries including Belarus.

Commercial Financing Options

Vendor Financing: Vendor financing covers options that include corporate financing via equity or loans provided from the NPP vendor. This is only viable for very large vendors or vendor coalitions. In some cases, the vendor can also be a conduit for government financing by arranging credit from affiliated banks and export credit agencies. Vendor financing options, if properly tailored, could serve as a mechanism to compete with sovereign nation vendors. This model can take multiple forms to include partial or full ownership by the vendor as well as transfer/return of any used nuclear fuel to the vendor nation, enabling the host nation to avoid the cost and challenge of developing a storage or disposal capability.[32] In some cases, the vendor may operate for a time and then transfer to the host nation once workforce capacity has grown ("Build-Own-Operate-Transfer" or BOOT) In other cases, the vendor retains all own/operate responsibilities and is simply providing energy output to the customer ("Build-Own-Operate" or BOO).

Investor Financing: Investor financing through special project financing vehicles. This form of financing has been used in energy investment but has not been used in nuclear project development. In this case, investors make a bet on the revenues from the resulting project (versus investing in the developers). This may be more challenging for advanced reactor developers given the higher uncertainty in plant reliability (capacity factor) for these advanced reactor designs.

Export-Import Bank: In the past, a primary source for financing foreign projects by U.S. companies was the U.S. EXIM Bank, chartered by the Export-Import Bank Act of 1945. The Bank is backed by the U.S. government's full faith and credit, providing support for U.S. exports to augment/supplement private sector finance and/or to counter foreign Export Credit Agency (ECA) financing (EXIM Bank 2021). In 2019, funding approvals from the Bank totaled $5.3 billion, placing the United States in the seventh position among foreign export credit agencies and dwarfed by the $33.5 billion allocated by China in that year (Akhtar 2022). Given the scale of most nuclear projects, the limited availability of ECA backing for U.S. vendors has been a significant cause of concern. Fortunately, in 2019, the Congress approved a long-term funding authority increase through 2027 capped at a level of $135 billion (total exposure) (Akhtar 2022).

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[32] Given the difficulty the United States has encountered in developing storage or disposal facilities for even domestic fuel, it is not likely that a U.S. vendor could offer the takeback for fuel from foreign reactors.

Findings and Recommendation

Finding 10-4: For U.S. vendors to better compete with state-owned or state-financed vendors in the dynamic international energy market, a technically and economically viable product must be established that could then be supported by a robust and reliable source of export credit financing. Non-U.S. vendors have more options for financing the export and deployment of advanced reactors than U.S. vendors. This imbalance will eventually reduce the competitiveness of the United States' advanced reactors in the international marketplace, which could limit the opportunities to build successful partnerships that the United States has used effectively to promote U.S. national security and global nuclear safety, security, and safeguards. Exploring non-standard financial mechanisms and ownership models, such as Build Own Operate (BOO) or Build Own Operate Transfer (BOOT), could be useful in non-Organisation for Economic Co-operation and Development (OECD) markets.

Finding 10-5: Most U.S. advanced reactor vendors will not be ready for international commercial deployment until after successful demonstrations in the United States and thus will be unlikely to tap export-import bank financing before a new authorization cycle is necessary. Given the political challenges that occurred from 2015 to 2019, vendors may not view this as a reliable source absent action by Congress to stabilize and expand funding further.

Recommendation 10-2: International nuclear projects by U.S. exporters are likely to require a financing package that reflects a blending of federal grants, loans, and loan guarantees along with various forms of private equity and debt financing. The Executive Branch should work with the private sector to build an effective and competitive financing package for U.S. exporters.

U.S. GOVERNMENT AND IAEA INITIATIVES

In line with the increased legal and financial support by the U.S. government for expanding the U.S. new and advanced reactor industry over the past decade, the U.S. government has created a number of programs to support U.S. vendors in marketing of their products internationally.

DOS Initiatives

The Department of State's Nuclear Future's Package aims to coordinate and intensify U.S. efforts to prepare the international market for U.S. reactor vendors and associated industry stakeholders. The Nuclear Future's Package contains three separate efforts: the Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) program, the Countering Insecure Floating Nuclear Power Plant Deployments (FNPP) program, and a pilot Countering the Strategic Deployment of Nuclear Energy-Related Disinformation program.

The FIRST program seeks to manage a partnership among U.S. government entities, the national laboratories, universities, industry, and other non-government organizations, primarily aimed at supporting the development of effective nuclear governance in potential nuclear newcomers. It contains a ten-module program for partners, including modules on nuclear security and safeguards (FIRST Program n.d.). The capacity-building activities and most high-level dialogues reportedly will focus exclusively on supporting the deployment of SMRs, with at least 17 countries as prospective partners. The FIRST program explicitly aims to support the IAEA Nuclear Infrastructure Milestones Approach (see below). The State Department has established partnerships with Kenya, Indonesia, and Latvia through the FIRST program.[33,34] The $25 million budget builds on the $5.3 million originally committed to the FIRST program announced earlier in 2021 (Office of the Spokesperson 2021a).

FFNPs have considerable potential for making an important contribution to the production of nuclear energy, including in developing markets. The Countering Insecure of FNPP Deployments project begins with the premise that some of the countries developing FNPPs, notably Russia, have rushed them to market without international agreement on a range of safeguards and other issues.[35] Similarly, the pilot project on disinformation aims to oppose misrepresentation of the cost of doing business with U.S. suppliers of nuclear technology. These latter two projects address concerns about the international competitiveness of U.S. new and advanced reactors and the possible erosion of international safeguards and security standards as a consequence of market expansion for some countries.

DOE Initiatives

DOE's National Nuclear Security Administration has initiated three programs:

1. *Civil Nuclear Security Project (CNSP):* This effort seeks to build relationships with U.S. nuclear energy industry vendors to support three main objectives: (1) improve security of future U.S. exports; (2) support nuclear security infrastructure development in newcomer countries; and (3) uphold the global nuclear security regime through IAEA collaboration.
2. *Nuclear Technology and Assistance Regulation (10 CFR Part 810):* NNSA supports regular vendor engagement and works to ensure familiarization with DOE statutory responsibilities for authorizing the transfer of unclassified nuclear technology and assistance to foreign atomic energy activities within the United States or abroad. These responsibilities and constraints are spelled out in 10 CFR Part 810.
3. *Proliferation Resistance Optimization (Pro-X):* NNSA supports collaborative efforts with operators, designers, and other stakeholders to improve proliferation resistance and optimization strategies for individual facility designs.

IAEA Initiatives

For newcomer countries, the IAEA has developed a "Milestones Approach" methodology of elements needed in the 10–15 years of preparatory work in establishing a new nuclear power program (or for expanding existing programs) and the even longer commitment required for the program itself. The three-phase approach covers 19 nuclear infrastructure issues that Member States must address, which includes nuclear security and safeguards, and provides the basis for the IAEA Integrated Nuclear Infrastructure Review (INIR) service. The approach emphasizes, moreover, that "[t]he use of nuclear material requires constant and strict attention to *nuclear safety*, *nuclear security*, and *safeguards* [italics in text]" (IAEA 2015, p. 2). The Milestones guidance document elaborates the safeguards and security milestones in different phases in developing a new nuclear power program (IAEA 2015, sec. 3.6 and 3.15

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[33] U.S. Department of State, 2022, "Joint Statement on the New Clean Energy and Nuclear security Collaboration under the Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) Initiative," https://www.state.gov/joint-statement-on-the-new-clean-energy-and-nuclear-security-collaboration-under-the-foundational-infrastructure-for-responsible-use-of-small-modular-reactor-technology-first-initiative.

[34] Partnership for Global Security, 2023, "An Unconventional Strategy for Effective Nuclear Export," https://partnershipforglobalsecurity.org/an-unconventional-strategy-for-effective-nuclear-export.

[35] For more on the considerable legal issues posed by FNPPs, see A. Popov, 2022, "Russian Vision of the Problems and Prospects of the International Legal Framework in the Context of Small Modular Reactors and Transportable Nuclear Power Units," Nuclear Law, The Hague, T.M.C. Asser Press, https://doi.org/10.1007/978-94-6265-495-2_3.

respectively; INSAG 2012). The Milestones Approach does not single out programs that would use more traditional reactor types or new and advanced reactors, but the IAEA has identified the Milestones Approach as the framework for Member States seeking new nuclear programs, including the deployment of SMRs (Kovachev 2019).

In March 2022, the IAEA announced its Nuclear Harmonization and Standardization Initiative (NHSI), which unlike the Milestones Approach more narrowly aims at "bringing together policy makers, regulators, designers, vendors and operators to develop common regulatory and industrial approaches to SMRs" (IAEA 2022; World Nuclear News 2022). The NHSI already has garnered approval from Canada and China among suppliers of nuclear technology (IAEA 2022; World Nuclear News 2022).

Finding and Recommendation

Finding 10-6: Increasing harmonization in developing and interpreting international nuclear export control guidelines as they apply to advanced reactors by nuclear suppliers will help equalize regulatory requirements facing U.S. and non-U.S. vendors.

Recommendation 10-3: The three lead U.S. export control agencies (Department of Energy, Nuclear Regulatory Commission, Department of Commerce) should continue to support initiatives within the International Atomic Energy Agency and Nuclear Suppliers Group (e.g., technical exchanges, guidance reviews, and regular meetings) to monitor and promote harmonized implementation and interpretation of export control, safety, security, and safeguards guidelines. Increased commitment of U.S. resources to the three lead export control agencies will be needed to support the work of the Nuclear Suppliers Group on new and advanced reactors, including resources for and leadership in a review of new materials and technologies in conjunction with an internal U.S. review of these items.

REFERENCES

Bowen, M., and P. Dabbar. 2022. "Reducing Russian Involvement in Western Nuclear Power Markets." Commentary. New York, NY: Columbia SIPA Center on Global Energy Policy. https://www.energypolicy.columbia.edu/research/commentary/reducing-russian-involvement-western-nuclear-power-markets.

Bureau of International Security and Nonproliferation. n.d. "Nuclear Cooperation Memoranda of Understanding (NCMOU)." *United States Department of State* (blog). https://www.state.gov/nuclear-cooperation-memoranda-of-understanding-ncmou.

Clagett, S. 2021. "Commerce Controls and the Nuclear Power Industry," Presented to the committee on October 4. https://www.nationalacademies.org/event/10-04-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-8#sectionEventMaterials. Available by request through PARO@nas.edu.

CRS (U.S. Congressional Research Service). 2019. "Nuclear Cooperation: Part 810 Authorizations." April 18. Paul K. Kerr and Mary Beth D. Nikitin. *In Focus* No. IF11183. https://crsreports.congress.gov/product/pdf/IF/IF11183.

Daniels, M. and J. Krige. 2022. "Chapter 3: The Cold War National Security State and the Export Control Regime." In *Knowledge Regulation and National Security in Postwar America*. Chicago: University of Chicago Press.

Department of Energy (DOE). 2020. *Restoring America's Competitive Nuclear Energy Advantage*. Department of Energy. https://www.energy.gov/sites/prod/files/2020/04/f74/Restoring%20America%27s%20Competitive%20Nuclear%20Advantage-Blue%20version%5B1%5D.pdf.

Donovan, J., and P.C. Vives. 2022. "Accelerating SMR Deployment: New IAEA Initiative on Regulatory and Industrial Harmonization." *International Atomic Energy Agency*, April 1. https://www.iaea.org/newscenter/news/accelerating-smr-deployment-new-iaea-initiative-on-regulatory-and-industrial-harmonization.

Energy Futures Initiative. 2017. *The U.S. Nuclear Energy Enterprise: A Key National Security Enabler*. Moniz, E., Kizer, A., Hezier, J. Washington DC: Energy Futures Initiative. https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2022/02/The-U.S.-Nuclear-Energy-Enterprise_A-Key-National-Security-Enabler_Report_August-2017.pdf.

Ford, M.J., and A. Abdulla. 2021. "New Methods for Evaluating Energy Infrastructure Development Risks." *Risk Analysis* 43:624-640. https://doi.org/10.1111/risa.13727.

Habighorst, P. 2021. "NRC Preparations for Advanced Reactor Exports." Presented to the committee, October 4. https://www.nationalacademies.org/event/10-04-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-8#sectionEventMaterials. Available by request through PARO@nas.edu.

Hamblin, J.D. 2021. "Chapter 1: The Have-Nots." In *The Wretched Atom: America's Global Gamble with Peaceful Nuclear Technology*. Oxford: Oxford University Press.

Hamre, J. 2015. *Sustaining American Leadership in the Nuclear Industry*. Stanford, CA: Hoover Institute Press.

Hamre, J.J. 2013. *Restoring U.S. Leadership in Nuclear Energy: A National Security Imperative*. Center for Strategic and International Studies. Washington, DC.

IAEA (International Atomic Energy Agency). 2019. *Communication Received from the Permanent Mission of Kazakhstan to the International Atomic Energy Agency Regarding Certain Member States' Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Materials, Software and Related Technology*. INFCIRC/254/Rev.11/Part 2. Vienna: International Atomic Energy Agency.

IAEA. 2021. *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, Reference Data Series No. 1*. Vienna: International Atomic Energy Agency.

Ichord, R.F. 2022. "Nuclear energy and global energy security in the new tripolar world order." Atlantic Council. https://www.atlanticcouncil.org/blogs/energysource/nuclear-energy-and-global-energy-security-in-the-new-tripolar-world-order.

IEA (International Energy Agency). 2022a. *World Energy Outlook 2022*. International Energy Agency: Paris. https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.

IEA. 2022b. *Nuclear Power and Secure Energy Transitions*. International Energy Agency: Paris. https://www.iea.org/reports/nuclear-power-and-secure-energy-transitions.

INSAG (International Nuclear Safety Group). 2012. *Licensing the First Nuclear Power Plant.* (INSAG-26). Vienna: International Atomic Energy Agency.

Kerr. P.K., M.B.D. Nikitin, and M. Holt. 2014. *Nuclear Energy Cooperation with Foreign Countries: Issues for Congress*. U.S. Congressional Research Service. https://sgp.fas.org/crs/nuke/R41910.pdf.

Lovering, J.R., A. Abdulla, and G. Morgan. 2020. "Expert assessments of strategies to enhance global nuclear security." *Energy Policy* 139:111306.

McIntosh, S. 2022. "Nuclear Liability and Post-Fukushima Developments." Pp. 249–269 in *Nuclear Law*. T.M.C. Asser Press, The Hague. https://doi.org/10.1007/978-94-6265-495-2_12.

MIT (Massachusetts Institute of Technology). 2003. *The Future of Nuclear Power: An Interdisciplinary MIT Study*. Boston MA: Massachusetts Institute of Technology.

NRCRIC (U.S. Nuclear Regulatory Commission Regulatory Information Conference). 2021. *M3 U.S. Regulatory Preparations for the Export of Advanced Reactors*. https://www.nrc.gov/docs/ML2122/ML21225A692.pdf.

Popov, A. 2022. "Russian Vision of the Problems and Prospects of the International Legal Framework in the Context of Small Modular Reactors and Transportable Nuclear Power Units." Pp. 45–54 in *Nuclear Law*. The Hague: T.M.C. Asser Press.

Schneider M., and A. Froggatt. 2022. *The World Nuclear Industry: Status Report 2022*. Paris. https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html#_idTextAnchor236.

Strangis, K. 2021. "Overview of 10 CFR Part 810 Program." Presented to the committee, October 5. https://www.nationalacademies.org/event/10-04-2021/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states-meeting-8. Available by request through PARO@nas.edu.

Stulberg, A., and J. Darsey. 2020. "Turning Rivals into Frenemies: Shifting U.S.–Russian Trajectories at the Nexus of Global Nuclear Commerce and Nonproliferation." PONARS Eurasia. https://www.ponarseurasia.org/turning-rivals-into-frenemies-shifting-u-s-russian-trajectories-at-the-nexus-of-global-nuclear-commerce-and-nonproliferation.

World Nuclear News. 2022. "IAEA Initiative to Accelerate Deployment of SMRs." *World Nuclear News*, July 6. https://www.world-nuclear-news.org/Articles/IAEA-initiative-to-accelerate-deployment-of-SMRs.

Appendixes

A

Summary of Advanced Reactor Design Concepts

Advanced reactor systems include small modular light water reactors as well as small modular reactor systems that use non-water coolants, so-called Generation-IV reactors (WNA 2020). In the following sections, general characteristics and representative examples of each reactor concept are described.

SMALL MODULAR LIGHT WATER REACTORS

Small modular light water reactors (LWRs) are based on the current large LWR technologies but have smaller and simpler system configurations. These designs are characterized by an electrical generating capacity of less than 300 MWe for a single reactor power module, with the major difference in comparison to large LWRs being the high degree of passive safety. The smaller thermal power allows the designer to simplify the engineering system and to eliminate active safety systems that require AC electrical power. Instead, passive safety systems rely on natural forces of pressure and gravity to provide the required water coolant flow through the reactor core, removing heat under normal operation as well as the residual decay heat after shutdown to guarantee long-term core cooling during off-normal transients. As an additional benefit, these designs can take advantage of the large operating experience of the current operating fleet.

The NuScale Power Module (NPM) design is the most mature small modular LWR design and is targeted for deployment in this decade as a source of electricity (NuScale Power 2021a). The NPM is a self-contained integral pressurized water reactor (PWR) module, and the reactor vessel and containment are designed to be manufactured in a factory, shipped to the plant site, and installed with other NPMs as part of an overall plant configuration. The current fuel assembly design for an NPM is a shortened version of a standard 17×17 PWR fuel assembly, with the uranium-dioxide fuel enriched to less than 5 percent ^{235}U. The current fuel cycle is designed to be once-through with refueling and inspection of the NPM every 18–24 months. Modules are sited below-grade in a seismically robust pool of water that acts as the ultimate heat sink. The NPM functions similarly to current LWRs, and each module contains both the primary and secondary side of the power cycle. Additionally, the NPM relies on natural circulation for core-cooling and heat transport to the steam generators with a Rankine steam-turbine power conversion system, making it more resilient to any accident. The NuScale reactor system design was recommended by the U.S. Nuclear Regulatory Commission (NRC) staff for its Design Certification (DC) for potential construction and operation in this decade (NuScale Power 2021b). The NRC granted the DC granted the DC in July 2022 (WNN 2022) and published in the Federal Register in January 2023. In December 2022, NuScale submitted a Standard Design Approval application to NRC for its updated design, which is based on a six-module configuration powered by an uprated 250 MWth (77 MWe) module (NuScale Power 2023). The design employs the same safety case and passive safety features approved by the NRC in 2020 with a power uprate and select design changes to support customers’ capacity needs.

LIQUID METAL–COOLED FAST REACTORS

Liquid metal-cooled fast reactors have evolved from early small demonstration plants (e.g., the sodium-cooled Experimental Breeder Reactor, EBR) (ANL 2020) and are a relatively mature design concept. The leading design concept uses liquid sodium as the coolant, although lead-cooled systems have also been designed and tested internationally. The sodium fast reactor (SFR) operates at high power density given the absence of a moderator and the superior heat removal capability of the liquid sodium coolant. The reactor operates near atmospheric pressure at outlet temperatures (500–600°C) far below the sodium boiling point (~900°C), a safety feature of the design. There are a few potential system designs: modular (50–100 MWe), pool-type (100–1500 MWe), or loop-type (600–1500 MWe). The designs under consideration today are small pool-type SFRs with inherent and passive safety features. These designs may include three coolant circuits: a sodium pool that cools the reactor core and an intermediate loop that separates the sodium pool for safety and transfers the heat to a third loop, which contains the working fluid for the power conversion system (e.g., Rankine steam-cycle). SFRs typically have higher thermal efficiencies (35–40 percent) than LWRs. U.S. designs are fueled with a metallic alloy of uranium and zirconium contained in steel cladding, which was successfully tested in the EBR. The metal alloy fuel has the advantage of having little stored thermal energy, and the core is designed to thermally expand under off-normal high-temperature conditions, providing a negative reactivity feedback to limit any power increase. In contrast, international programs (e.g., France, Japan) use uranium dioxide fuels.

Some small modular SFR concepts, like the GE PRISM design (Triplett, Loewen, and Dooies 2012), recycle their fuel and thus operate on a fuel cycle in which the fuel contains both uranium and plutonium. Larger SFR designs that do not contain recycled plutonium and achieve long-lived fuel cycles (e.g., decades) are under development (e.g., Hejzlar et al. 2013). However, these designs require advances in fuel and materials technology to meet performance objectives.

Most recently, TerraPower, with GE-Hitachi Nuclear Energy and Bechtel as major subrecipients, is developing the Natrium reactor (TerraPower 2020). Natrium™ is a pool-type SFR combined with a molten salt thermal energy storage system as an intermediate loop. The design has a 345 MWe nuclear island with thermal energy storage that can increase output to 500 MWe of power for up to five hours when needed. The nuclear reactor and its supporting safety systems are decoupled from the energy storage system and the balance of plant. This type of design can provide flexible power operations and reduce costs by allowing for the use of non-safety-grade components for the balance of plant. The Natrium design can be optimized for specific markets such as electrical energy or process heat applications (e.g., hydrogen production). This plant is planned for demonstration at the end of this decade.

HIGH-TEMPERATURE GAS-COOLED REACTOR

High-temperature gas-cooled reactors (HTGRs) are an evolutionary reactor design of the gas-cooled reactors in operation today, such as the UK Magnox reactors (WNA 2021a) and the Chinese HTR-PM (WNN 2021a), and are a relatively mature design. The HTGR design is a graphite moderated thermal reactor with a low power density and cooled by high-pressure gas. These reactors use prismatic graphite blocks or spherical graphite pebbles as fuel assemblies within a graphite core structure. Major differences in comparison to large LWRs include use of helium (an inert gas that overcomes corrosion issues) as the heat transfer coolant, higher outlet temperatures, and higher thermal efficiencies (~1000 K), as well as enhanced safety in the fuel design. The higher outlet temperature enables heat to be supplied for a variety of process heat applications. The fuel design uses uranium fuel formed into “poppy seed”–size particles, termed TRi-structural ISOtropic (TRISO) fuel particles. The current TRISO particle fuel is made up of a uranium-oxy-carbide (UCO) fuel kernel encapsulated by three layers of dense carbon and silicon carbide (SiC) (EPRI 2019). These particles provide the primary containment of the fission products and are then formed into cylindrical compacts in prismatic graphite blocks or spherical graphite pebbles (billiard ball size). The HTGR uses passive safety cooling systems that rely on heat conduction, thermal radiation, and natural circulation to remove residual decay heat after reactor shutdown, rather than active systems used in current large LWR technologies. HTGRs can be designed to operate as a base load or a flexible load on the grid.

The X-energy HTGR design, Xe-100, is targeted for demonstration in this decade (X-energy 2021a). Each reactor module is 80 MWe, with the plant designed for four reactor modules, comprising a 320 MWe power plant. X-energy is partnering with Dow to demonstrate its first plant at one of Dow's industrial sites in the U.S. Gulf Coast (X-energy, 2023). The reactor will be fueled by X-energy fuel, TRISO-X, in the form of thousands of pebbles, which slowly circulate through the core to allow for on-line refueling and on-site fuel storage. The reactor helium coolant outlet temperature is 700 °C. The helium coolant transports the reactor heat to a steam generator, and the plant output options include direct steam heat or electricity production through a Rankine steam-turbine power conversion system. The reactor design incorporates factory-produced commercial components and is planned to be factory assembled and road transportable, with an expected construction time of four years. X-energy is currently engaged with NRC staff on preapplication activities (Bowers, van Staden, and Medlock 2018; U.S. NRC 2021b) and with Canadian Nuclear Safety Commission on a Vendor Design Review for demonstration in Canada at the Ontario Power Generation Darlington site (X-energy 2021b).

GAS-COOLED FAST REACTOR

The gas-cooled fast reactor (GFR) design concept has been developed by researchers in the United States (e.g., General Atomics EM2, Choi and Schleicher 2017; Choi et al. 2021) and internationally (e.g., French CEA Allegra, Dumaz et al. 2007).GFR design concepts employ a low-power-density fast reactor cooled by high-pressure helium. To date, a demonstration plant has not been planned to be built at any scale, and the design is not considered a mature concept. Barriers to demonstration include fuel qualification and developing a method to handle gaseous fission product buildup in the fuel. Uranium carbide (UC) fuels (e.g., EM2's UC fuel in SiC cladding) have been considered for use in this design because they meet the high fissile fuel requirements for a fast reactor with a smaller core volume. To accommodate the large buildup of fission product gases in the fuel, design concepts propose to use vented fuel rods or larger fuel rod gas plenum volumes as in the SFR. Conceptual designs have specified a core that contains fuel and structures that need to accommodate the high operating temperatures (700–850°C). Outlet temperatures for most proposed designs of this reactor type may be as high as 850°C, and the power conversion system can be either a Brayton power cycle (direct or indirect) or a more traditional Rankine steam power cycle.

FLUORIDE-SALT HIGH-TEMPERATURE REACTOR

The fluoride salt-cooled high-temperature reactor (FHR) is a unique thermal reactor concept that uses TRISO particle fuel technology in combination with a liquid fluoride salt coolant at high temperatures (outlet temperatures 650–700°C) and ambient pressure (Forsberg et al. 2015). The fluoride-based salt is a mixture of lithium fluoride and beryllium fluoride (i.e., FLiBe), which has superior heat transfer characteristics compared to helium, resulting in lower fuel operating temperatures. The reactor is designed to operate at a power density at least four times higher than a HTGR. The graphite moderator can be arranged in a prismatic or pebble core design. The FHR is a relatively new concept (2010), but the pebble bed core design has been advanced more than the prismatic concept. A major challenge to be addressed is gaining operational experience with the FLiBe coolant given its chemical composition with beryllium and the need to maintain worker safety. Kairos, the private company advancing this pebble bed fueled and molten salt cooled design (Kairos Power 2021a), plans to build a prototype test reactor (Hermes) sited in Tennessee near Oak Ridge National Laboratory (Kairos Power 2021b). Kairos plans to demonstrate the performance of this design concept with the Hermes test reactor under prototypic operating conditions that allow for integral testing of its safety systems. The Kairos development approach is unique—that is, at each stage of development, an iterative process of "design, build, and test" is employed to obtain key test data that can improve the reactor design.

MOLTEN SALT REACTOR

The molten salt reactor (MSR) is a concept that has been considered viable since a small experimental reactor was operated at Oak Ridge National Laboratory in the 1960s (ORNL n.d.). This type of reactor uses a molten salt as both the coolant and the fuel—that is, the uranium fuel is dissolved in the molten salt. Both thermal and fast MSRs are under development, and all MSR design concepts are quite unique with the common element being dissolved fuel in molten salt. The thermal systems use a fluoride salt composition with graphite or another material as a moderator. The fast reactor concept uses chloride salts without a moderator. Power densities are generally similar to LWRs for thermal reactor designs and to SFRs for fast reactor designs. Fluoride and chloride salts have high melting points; thus, reactor inlet coolant temperature for these systems must be above 500 °C to prevent freezing during normal operation as well as operational transients. While a variety of conceptual designs have been proposed (WNA 2021b), they are relatively immature and require significant research and development before a demonstration plant is possible, particularly to address issues related to materials compatibility.

Terrestrial Energy is developing a thermal spectrum Integral Molten Salt Reactor (IMSR) that is 195 MWe, with a 44 percent thermal efficiency, and uses uranium enrichments of about 5 percent, which can be supplied by today's supply chain (Terrestrial Energy 2021). They are also working on a 390 MWe version. Terrestrial Energy focuses primarily on the Canadian market, where their design is under review by the Canadian regulator and has been selected by Ontario Power Generation for consideration for their Darlington site (Terrestrial Energy 2020). An advantage of molten salts is their high heat capacity, and Terrestrial Energy is planning to be able to use 700 °C heat for industrial heat applications in addition to power generation (Terrestrial Energy 2021).

MICRO-SCALE NUCLEAR REACTORS

Very small reactors with power output less than 10 MWe (so-called microreactors) are now under development for applications away from the main electrical grid. These microreactors could provide electricity and/or heat for a range of microgrid applications, such as remote communities, industrial complexes, and military and government installations that need a secure, resilient energy supply (Buongiorno et al. 2021a). To maximize their utility and minimize their cost, microreactors are being designed with several key features, including transport of the complete system to the site where it will be used, minimal on-site construction activities, operation with minimal on-site staffing, and coupling to compact power conversion systems such as supercritical CO_2 Brayton cycles (Buongiorno et al. 2021b). As discussed in Chapter 7, regulatory challenges exist for these microreactor designs—for example, autonomous operations, security issues, and transport of fueled microreactors to and from the site of operations. Microreactor conceptual designs cover the range of larger advanced reactor designs—for example, liquid metal-cooled and gas-cooled reactors, thermal and fast neutron spectrum reactors (Palmieri, Corradini, and Wilson 2021). Some designs, based on space reactor application, use heat pipe technology for cooling the reactor core and transporting heat to the power conversion system. Examples of these microreactors include the Westinghouse eVinci and the Oklo Aurora (Westinghouse 2019; U.S. NRC 2020).

The eVinci microreactor, designed by Westinghouse, is targeted for operation in the next decade to generate heat and electricity in remote communities, as well as commercial and government installations that are self-contained on a local microgrid. The reactor is designed to be manufactured and fueled in a factory environment and transported to a proposed site in standard shipping containers. The design has a scalable power generation ranging from 1 – 5 MWe. The eVinci concept is an evolutionary design based on the Los Alamos National Laboratory *Megapower* reactor, which was built and tested for space applications. The reactor core is designed to use conventional uranium oxide fuel (or TRISO-UCO fuel) with the fuel encased in a solid monolithic metal block with minimal moving parts for reactor control and shutdown. This uranium-fueled reactor does not use a bulk primary coolant. Instead, heat is removed from its core using heat pipes, thereby limiting the number of moving parts and providing overall plant simplicity. The heat pipes use a liquid metal as the working fluid at low pressures. They are embedded in the solid monolithic core to transfer the reactor heat from the core region to a Brayton power conversion system. The design uses the inherent safety features in the fuel, moderator, and heat pipes to enhance safety and self-regulation capability—for example, long-term cooling by conduction to the surroundings. The reactor core is designed to operate for more than three years without refueling and maintenance. The reactor module is also designed to require a minimal number of on-site operational personnel with advanced instrumentation that allows for on-site as well as remote system monitoring.

REFERENCES

ANL (Argonne National Laboratory). 2020. “Fast Reactor Technology.” Reactors Designed by Argonne National Laboratory, 2020. https://www.ne.anl.gov/About/reactors/frt.shtml.

Bowers, H., M. van Staden, and C. Medlock. “X-Energy Xe-100 Reactor Initial NRC Meeting.” Presented at the Xe-100 Reactor Initial NRC Meeting, September 11, 2018. https://www.nrc.gov/docs/ML1825/ML18253A109.pdf.

Buongiorno, J., R. Freda, S. Aumeier, and K. Chilton. 2021a. A Strategy to Unlock the Potential of Nuclear Energy for a New and Resilient Global Energy-Industrial Paradigm. *The Bridge* 51(2):48–56. https://www.nae.edu/255810/A-Strategy-to-Unlock-the-Potential-of-Nuclear-Energy-for-a-New-and-Resilient-Global-EnergyIndustrial-Paradigm.

Buongiorno, J., B. Carmichael, B. Dunkin, J. Parsons, and D. Smit. 2021b. Can Nuclear Batteries Be Economically Competitive in Large Markets? *Energies* 14(14). https://doi.org/10.3390/en14144385.

Choi, H., and R.W. Schleicher. 2017. The Energy Multiplier Module (EM2): Status of Conceptual Design. *Nuclear Technology* 200(2):106–24. https://doi.org/10.1080/00295450.2017.1364064.

Choi, H., J. Bolin, O. Gutierrez, J. O’Hara, R. Hom, R. Schleider, et al. 2021. *The Fast Modular Reactor (FMR)—Development Plan of a New 50 MWe Gas-cooled Fast Reactor*. American Nuclear Society Annual Meeting, Vol. 124

Dumaz, P., P. Allègre, C. Bassi, T. Cadiou, A. Conti, J.C. Garnier, J.Y. Malo, and A. Tosello. 2007. Gas-Cooled Fast Reactors—Status of CEA Preliminary Design Studies. *NURETH-11* 237(15):1618–1627. https://doi.org/10.1016/j.nucengdes.2007.03.018.

EPRI (Electric Power Research Institute). 2019. “Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance: Topical Report EPRI-AR-1(NP).” Technical Report 3002015750. Palo Alto, CA: Electric Power Research Institute. https://www.epri.com/research/products/000000003002015750.

Forsberg, C., L. Hu, P. Peterson, and K. Sridharan. 2015. *Fluoride-Salt-Cooled High-Temperature Reactor (FHR) for Power and Process Heat*. Massachusetts Institute of Technology.. https://doi.org/10.2172/1183687.

Hejzlar, P., R. Petroski, J. Cheatham, N. Touran, M. Cohen, B. Troung, R. Latta, et al. 2013. “TerraPower, LLC Traveling Wave Reactor Development Program Overview.” *Nuclear Engineering and Technology* 45(6): 731–44. https://doi.org/10.5516/NET.02.2013.520.

Kairos Power. 2021a. “Technology.” https://kairospower.com/technology.

Kairos Power. 2021b. “Governor Lee, Commissioner Rolfe Announce Kairos Power to Establish Low-Power Demonstration Reactor in Oak Ridge.” https://kairospower.com/external_updates/governor-lee-commissioner-rolfe-announce-kairos-power-to-establish-low-power-demonstration-reactor-in-oak-ridge.

NuScale Power. 2023. “NuScale Builds Upon Unparalleled Licensing Progress with Second Standard Design Approval Application Submittal.” https://www.nuscalepower.com/en/news/press-releases/2023/nuscale-builds-upon-unparalleled-licensing-progress-with-second-standard-design-approval.

NuScale Power. 2021a. “How the NuScale Module Works.” Technology Overview. https://www.nuscalepower.com/technology/technology-overview.

NuScale Power. 2021b. “NRC Interaction.” Licensing. https://www.nuscalepower.com/technology/licensing.

ORNL (Oak Ridge National Laboratory). 2023. “Molten Salt Reactor—History.” Nuclear Energy and Fuel Cycle Division. https://www.ornl.gov/molten-salt-reactor/history.

Palmieri, T.M., M. Corradini, and P. Wilson. 2021. *Analysis of the Case for Federal Support of Micro-Scale Nuclear Reactors to Provide Secure Power at U.S. Government Installations*. Madison, WI: University of Wisconsin-Madison, Institute for Nuclear Energy Systems.

TerraPower. 2020. “Natrium,” https://natriumpower.com.

Terrestrial Energy. 2020. “Terrestrial Energy IMSR Power Plant Selected by OPG for Further Evaluation.” *Terrestrial Energy*, October 6. https://www.terrestrialenergy.com/2020/10/06/terrestrial-energy-imsr-power-plant-selected-by-opg-for-further-evaluation.

Terrestrial Energy. 2021. “IMSR Technology,” https://www.terrestrialenergy.com/technology.

Triplett, B.S., E.P. Loewen, and B.J. Dooies. 2012. PRISM: A Competitive Small Modular Sodium-Cooled Reactor. *Nuclear Technology* 178(2):186–200. https://doi.org/10.13182/NT178-186.

U.S. NRC (U.S. Nuclear Regulatory Commission). 2020. “Aurora—Oklo Application.” Combined License Applications for New Reactors, 2020. https://www.nrc.gov/reactors/new-reactors/col/aurora-oklo.html.

U.S. NRC. 2023. “Xe-100.” Pre-Application Activities. https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/xe-100.html.

Westinghouse (Westinghouse Electric Company, LLC). 2019. “Westinghouse eVinci Micro Reactor,” https://www.westinghousenuclear.com/Portals/0/new%20plants/evincitm/GTO-0001_eVinci_flysheet_RSB_03-2019_003.pdf?ver=2019-04-04-140824-613.

WNA (World Nuclear Association). 2020. “Generation IV Nuclear Reactors.” https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx.

WNA. 2021a. “Nuclear Power in the United Kingdom.” Country Profiles. https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-kingdom.aspx.

WNA. 2021b. “Molten Salt Reactors.” Current and Future Generation. https://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx.

WNN (World Nuclear News). 2021a. “Hot Functional Testing of HTR-PM Reactors Starts.” *World Nuclear News*, January 4. https://world-nuclear-news.org/Articles/Hot-functional-testing-of-HTR-PM-reactors-starts.

WNN. 2022. “U.S. Regulator to Issue Final Certification for NuScale SMR.” *World Nuclear News.* August 2. https://www.world-nuclear-news.org/Articles/US-regulator-to-issue-final-certification-for-NuSc#:~:text=The%20US%20Nuclear%20Regulatory%20Commission,be%20certified%20by%20the%20NRC.

X-energy. 2023. “Dow and X-Energy Advance Efforts to Deploy First Advanced Small Modular Nuclear Reactor at Industrial Site Under DOE’s Advanced Reactor Demonstration Program.” X-Energy. March 1. https://x-energy.com/media/news-releases/dow-and-x-energy-advance-efforts-to-deploy-first-advanced-small-modular-nuclear-reactor-at-industrial-site-under-does-advanced-reactor-demonstration-program.

X-energy. 2021a. “Reactor: Xe-100.” https://x-energy.com/reactors/xe-100.

X-energy. 2021b. “Empowering Canada.” https://x-energy.com/canada.

B

Examples of Technology Development Gaps for Advanced Reactors

In general, the technology development gaps identified in Table 2-4 (see Chapter 2) for the higher maturity advanced reactor technologies are related to licensing qualification of unique systems and extension to new performance regimes—for example, development and qualification of unique reactor components, qualification of improved fuels and materials for higher burnup. In contrast, the technology development gaps for the lower maturity advanced reactor technologies are related to the viability and performance confirmation of key reactor features—for example, materials compatibility and corrosion behavior in a radiation field; demonstration of materials to show strength, corrosion resistance, and irradiation stability during operation; demonstration of tritium mitigation by control and monitoring; and integral performance of passive safety systems. The following sections provide a few specific examples where further technology development is required for particular reactor designs.

SMALL MODULAR LIGHT-WATER REACTORS—DEVELOP AND QUALIFY UNIQUE COMPONENTS

Small modular light water reactor (LWR) designs are largely based on current LWR technologies but incorporate passive safety systems to accomplish their safety functions, using smaller and simpler configurations with unique components. To confirm that the safety function is satisfied, the vendor must develop the component design, identify a supplier for these unique components, and work with the supplier to perform qualification testing to confirm acceptable performance before the plant is put into operation.

The NuScale Power Module (NPM) design is a good example of this because it has addressed the most risk-significant scenarios that arise using passive safety systems that rely on design and operational simplicity and redundancy (U.S. NRC 2020). Rather than active systems with pumps and valves, each NPM relies on four passive Emergency Core Cooling System (ECCS) valves that open when appropriate safety signals are received or when electric power is lost. Successful natural circulation cooling of the core is provided if one-of-two reactor vent valves open and one-of-two reactor recirculation valves open. The safety performance of this passive ECCS design is highly dependent on ensuring reliable operation of these valves. NuScale is working with the supplier to perform extensive qualification testing of this unique component, with an objective of providing confidence in the ability of the valves to maintain their required performance after extended periods in an operational environment. Such testing considers the possibility of degradation mechanisms such as deposits, precipitates, and fouling over time in the presence of boric acid in a high temperature and radiation environment. The results of this testing would be used to confirm acceptable performance in the next couple of years prior to issuance of the combined operating license by the U.S. Nuclear Regulatory Commission.

SODIUM FAST REACTOR–METALLIC FUEL QUALIFICATION

Fuel is the heart of all the nuclear reactor systems where the defense-in-depth principles and safety systems are designed based on it. While traditionally treated as a low-cost item as part of the nuclear power plant total cost, nuclear fuel dictates the reactor power density as well as nuclear plant construction requirements. The Natrium sodium fast reactor (SFR) demonstration plant is planned to start operation with a metallic fuel form that has been previously developed and has demonstrated a high-level of technical readiness (TerraPower 2021). This metallic fuel uses sodium inserted in the gap between the fuel cladding and the metallic fuel itself to better control the gap thermal resistance and to minimize peak fuel temperature throughout the fuel lifetime. This fuel has been successfully tested and used in past U.S. SFRs, such as Experimental Breeder Reactor-II (EBR-II) and Fast Flux Test Facility (FFTF). This fuel design also has developed an extensive body of empirical fuel performance data, which can assist in making a solid licensing case for reactor startup.

At the same time, TerraPower is developing an improved fuel design that removes the internal sodium-bond within the gap and uses fuel with an annular hole, which can better compensate for thermal effects as well as fuel burnup. This design change will also allow longer fuel lifetimes and higher plant thermal efficiency. This advanced fuel form needs to be qualified by insertion and testing of fuel pins and fuel assemblies into the reactor core to gather needed fuel performance data for design confirmation and regulatory approval. It will take a few years to convert from the sodium-bonded metallic fuel to this new annular fuel form.

The initial sodium-bonded metallic fuel design was not approved for direct disposal into Yucca Mountain because of the the presence of sodium. While TerraPower and national laboratory researchers feel that there is a technical case for direct disposal of this startup fuel, committee members note that alternatives exist if direct disposal is not approved by the regulator—for example, pyro-processing of this sodium-bonded fuel as is being done for the EBR-II reactor fuel (Hall, He, and Pan 2019). The processed fuel material would be acceptable for repository disposal (Ebert 2005). This waste management issue is discussed in detail in the companion National Academies study, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors* (NASEM 2022).

GAS REACTOR AND MOLTEN SALT REACTORS—DEMONSTRATION OF PASSIVE SAFETY SYSTEMS

Advanced reactor designs have incorporated passive safety systems using natural circulation for decay heat removal and long-term cooling. This approach to overall plant design allows for fewer auxiliary components or systems. These designs aim to demonstrate that long-term cooling can be accomplished without the need for AC power and can allow for extended coping times during transients and accidents (such as station blackout). This approach to long-term cooling has been taken in small modular LWRs (e.g., NuScale Decay Heat Removal System) as well as more mature non-LWR designs (e.g., SFR Direct Reactor Auxiliary Cooling System—DRACS; Groth et al. 2015). Such an approach is also part of the high-temperature gas-cooled reactor, the gas fast reactor design, and the various unique molten salt reactor designs, but actual integral testing would be required to demonstrate acceptable behavior for less mature concepts.

Natural circulation loops have been used, relying on natural forces (e.g., gravity and density difference) to efficiently transport heat without the need for active power sources. In advanced reactor designs, they have emerged as a leading focus area for passive safety, offering a solution to long-term core cooling and decay heat removal. These systems have become an integral part of the design, requiring no human intervention during an accident or transient (Lisowski et al. 2014). Of the concepts under consideration, several use water as a primary working fluid where operating conditions are expected to reach saturation. The venting of steam into the atmosphere serves as the ultimate heat sink, and hence these designs operate at low pressures only, requiring a resupply of water to the system after several days. Experimental test beds at Department of Energy national laboratories have been established for passive decay heat removal systems for these reactor technologies (ANL 2016). Reduced-scale engineering demonstrations are now being conducted over the next couple of years to understand the integrated behavior of the system prior to scale-up to a performance demonstration of commercial size.

REFERENCES

ANL (Argonne National Laboratory). 2016. “The NTSF at Argonne: Passive Safety and Decay Heat Removal for Advanced Nuclear Reactor Designs.” Nuclear Engineering Division. https://www.ne.anl.gov/capabilities/rsta/nstf/index.shtml.

Ebert, W.L. 2005. *Testing to Evaluate the Suitability of Waste Forms Developed for Electrometallurgically Treated Spent Sodium-Bonded Nuclear Fuel for Disposal in the Yucca Mountain Repository*. Argonne, IL: Argonne National Laboratory. https://publications.anl.gov/anlpubs/2006/01/55340.pdf.

Groth, K.M., M.R. Denman, T.B. Jones, M. Darling, and G.F. Luger. 2015. *Proof-of-Concept Accident Diagnostic Support for Sodium Fast Reactors*. Zurich, Switzerland. https://www.osti.gov/biblio/1258246.

Hall, N., X. He, and Y.-M. Pan. 2019. *Disposal Options and Potential Challenges to Waste Packages and Waste Forms in Disposal of Spent (Irradiated) Advanced Reactor Fuel Types*. San Antonio, TX: Center for Nuclear Waste Regulatory Analysis. https://www.nrc.gov/docs/ML2023/ML20237F397.pdf.

Lisowski, D.D., O. Omotowa, M.A. Muci, A. Tokuhiro, M.H. Anderson, and M.L. Corradini. “Influences of Boil-off on the Behavior of a Two-Phase Natural Circulation Loop.” *International Journal of Multiphase Flow* 60(April 1, 2014):135–48. https://doi.org/10.1016/j.ijmultiphaseflow.2013.12.005.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2022. *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.

U.S. NRC (U.S. Nuclear Regulatory Commission). 2020. “Design Certification Application – NuScale.” Small Modular Reactors (LWR designs). https://www.nrc.gov/reactors/new-reactors/smr/nuscale.html.

TerraPower. 2021a. “Additional TerraPower Information for Review Committees.” TerraPower, LLC.

C

Summary of Historical and Lessons-Learned Factors from the Department of Energy Office of Nuclear Energy–Funded Research and Development Programs in Support of Advanced Nuclear

The Department of Energy Office of Nuclear Energy (DOE NE) reactor technology research and development (R&D) portfolio has grown dramatically in scale since 1998, the year it reached its nadir. In 1998, there was essentially no funding for reactor technology R&D apart from ~$12 million ($ 2012) for university research program support of research and training reactors on university campuses. The only significant activity was continued work to decommission the Experimental Breeder Reactor (EBR-II) and sustain the nuclear infrastructure at Idaho National Lab (DOE 2021). The funding landscape has changed dramatically since this low point, with fiscal year 2021 funding reaching >$1.3 billion (real $ 2012), ~$800 million of which is focused on development of new fuels, waste management, advanced reactor development and sustaining the existing fleet of light water reactors (Figure C-1).

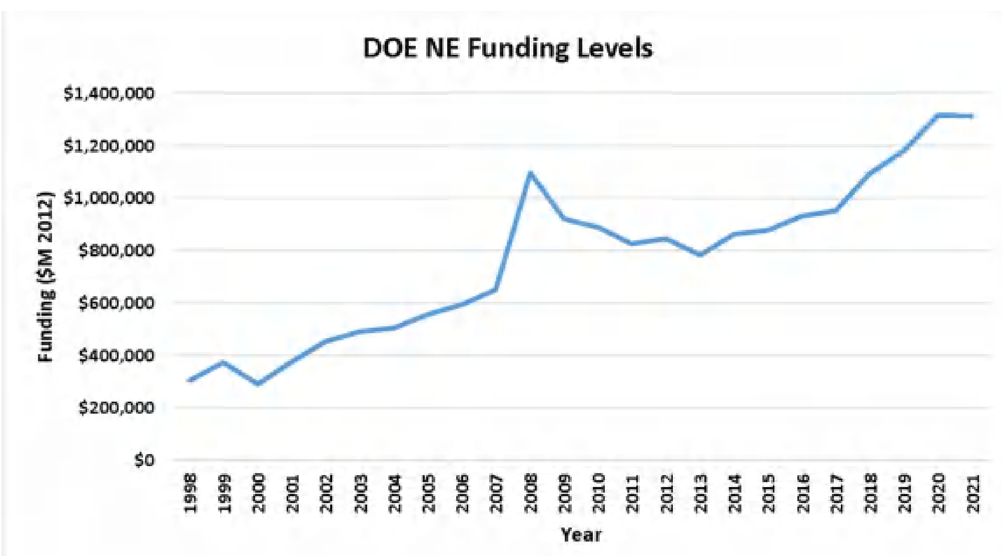

FIGURE C-1 DOE NE funding levels since 1998 ($ million 2012).
NOTE: The significant rise shown between 2008–2010 includes budget stimulus funding.
SOURCE: Committee generated using public budgets available at https://www.energy.gov/cfo/office-chief-financial-officer.

Despite this >400 percent funding growth, there have been few successes to point to in the demonstration of new nuclear generation technologies in the past 20+ years. A recent study indicated that for DOE NE funded programs since 1998,

> Numerically, more than half have been dedicated to advanced nuclear initiatives: on average, these have lasted less than 5 years and cost less than $160 million each. Using DOE's own roadmaps as a guide, these are of neither the duration nor the funding level necessary to develop a non-light water reactor. (Abdulla et al. 2017)

Construction and deployment of radioisotope production facilities such as SHINE, funded through the National Nuclear Security Administration (NNSA) and the recent development of the NASA funded Kilopower Reactor using Stirling Technology (KRUSTY) for space applications indicate that technical challenges in the nuclear domain can be met and new technologies can be demonstrated. But larger development efforts supported (and often managed) by DOE NE that may allow nuclear to play a larger role in decarbonization have not led to the deployment of a new reactor design concept in the United States, with frequent program starts and stops as administrations change and research focus waxes and wanes (Ford et al. 2017). Figure C-2 provides an indication of the program breakdown for the past 23 years.

An analysis of all programs does point to at least partial success in two projects. The first was the development of accident tolerant fuels, an effort that has come at significant cost, with over $1 billion invested in advanced fuels since 2003. The crown jewel of this effort is TRISO fuel, which has become a dominant fuel form in many advanced reactor designs. It remains to be seen if this fuel will prove affordable and sustainable in the long term, because none of the designs that anticipate use of this fuel have yet been demonstrated and a reliable commercial supply of High Assay Low Enriched Uranium ("HALEU") needed to develop a sustainable TRISO fuel cycle faces regulatory and policy challenges. It does promise to have safety advantages and may allow for longer time span for fuel usage in a reactor before refueling.

The other was the NP 2010 Program, which began in 2001 and succeeded in supporting two light water reactor designs through the development, licensing, and siting process—that is, Westinghouse AP1000 and the GE-Hitachi Economic Simplified Boiling Water Reactor (ESBWR). The program had four goals (Longnecker and Associates 2012):

1. Evaluate the business case for building new nuclear power plants.
2. Identify sites for new nuclear power plants.
3. Demonstrate untested regulatory processes (Combined Operating License process).
4. Develop advanced nuclear plant technologies.

The program received a total of >$725 million, and ultimately helped improve readiness for deployment of these Generation III+ designs. Reflecting success in meeting at least two of the goals of this DOE support effort (1 and 2), nuclear vendors and utilities saw viability in deploying the next generation of LWR designs and construction began in 2008 on two Westinghouse AP1000 plants at Summer, South Carolina following the new combined operating license (COL) process. This was followed in 2013 by construction start at the Vogtle site in Georgia. The plants were able to obtain COLs, reflecting the successful exercise of the regulatory process (3), albeit at great expense. Given that the Summer plant project ultimately was cancelled and the Vogtle plants are far behind schedule and over budget, it is highly unlikely that these designs will be exploited in further new construction in the United States.[1] Thus, the implicit objective of the program, demonstrating a pathway for new construction, was not a success owing to project management issues, which will be discussed in greater detail in Chapter 6.

[1] Note: Four AP1000 plants were constructed in China, at Sanmen site in Zhejiang, and Haiyang site in Shandong.

FIGURE C-2 Department of Energy programs relevant to nuclear energy technology development and deployment and approximate level of funding, 1998–2015.
SOURCE: A. Abdulla, M.J. Ford, M.G. Morgan, and D.G. Victor, 2017, "A Retrospective Analysis of Funding and Focus in US Advanced Fission Innovation," *Environmental Research Letters* 12(8):084016, https://doi.org/10.1088/1748-9326/aa7f10. CC BY 3.0.

The NP2010 effort did show that DOE can support development and deployment of nuclear technologies through to actual construction. This is, however, not the case with another technology development effort which began not long after initiation of the NP2010 effort—the Next Generation Nuclear Plant (NGNP) Program. The NGNP Program aimed to develop a high temperature gas reactor to generate both electricity and high temperature process heat for industrial applications, with construction of the first unit to begin in 2017. After eight years and $640 million in funding, DOE NE cancelled further development efforts owing to an inability to successfully partner with industry in the deployment phase of the project for a specific reactor design. A 2014 report from the Government Accountability Office summarized the project as follows:

> Among the advanced reactor technologies that NE's R&D currently supports, the high-temperature gas-cooled reactor is the technology that is most likely to be deployed and commercialized in the near term, according to an NE planning document. NE officials said this likelihood is based on the wide range of potential industry market applications and because of substantial government investments in the technology's development. NE has been pursuing this technology under the Next Generation Nuclear Plant (NGNP) Project, as established by the Energy Policy Act of 2005 (EPAct 2005). Under EPAct 2005, DOE is to deploy a prototype reactor for NGNP by the end of fiscal year 2021. However, in 2011, DOE decided not to proceed with the deployment phase of this project, citing several barriers. For example, NE and industry have been unable to reach an agreement on a cost-share arrangement to fund the deployment phase because of a disagreement on the applicable cost-share levels and how and when the cost-share would be applied to specific activities or project phases. Although NE continues to conduct R&D for the NGNP Project, it has not developed a strategy to overcome the cost-share issue and other barriers to resuming the deployment phase of the project. (GAO 2014)

Understanding the differences in the structure of these two programs may be critical in evaluating performance risk in the current advanced reactor development program. The structure of the NGNP Program was spelled out in March 2008 with issuance of the Preliminary Project Management Plan (INL 2008). The status of the program was updated in a 2010 report to Congress and was again detailed in a 2011 INL Report that summarized the challenges the program faced and the rationale for effectively cancelling the program prior to the demonstration phase (GAO 2014, Demick 2011).

The NP2010 Program, which ultimately led to the commercial development of a new reactor design (AP1000), was apparently better supported by industry, more likely to lead to deployment,[2] and focused on risk reduction in modular design, and employment of the 10CFR Part 52 regulatory process. Nevertheless, the root causes of the Summer project cancellation and Vogtle schedule delays and cost overruns also requires an assessment of these programs. This would be beneficial, emphasizing a review of programs differences tied to program duration, vendor/industry support, design risk, control of intellectual property, and cost share parameters. The NP2010 program ended prior to full execution of the Summer and Vogtle builds. Perhaps an extension of government support, to include construction and initial commercial deployment may be considered for the Advanced Reactor Demonstration Program (ARDP). Understanding these issues and factoring them into program design may be crucial in ensuring the success of the ARDP.

REFERENCES

Abdulla, A, M Ford, M G Morgan, and D G Victor. 2017 "A Retrospective Analysis of Funding and Focus in US Advanced Fission Innovation." *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/aa7f10.

Demick, L.E. 2011. *NGNP Project 2011 Status and Path Forward*. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1035900. INL/EXT-11-23907.

DOE. 2021. "Budget (Justification & Supporting Documents)." https://www.energy.gov/cfo/listings/budget-justification-supporting-documents.

Ford, M.J., A. Abdulla, M.G. Morgan, and D.G. Victor. 2017. "Expert Assessments of the State of U.S. Advanced Fission Innovation." *Energy Policy* 108(September):194–200. https://doi.org/10.1016/j.enpol.2017.05.059.

Government Accountability Office (GAO) 2014. "Advanced Reactor Research: DOE Supports Multiple Technologies but Actions Needed to Ensure a Prototype is Built." https://www.gao.gov/assets/gao-14-545.pdf

INL. 2008. *Next Generation Nuclear Plant Project Preliminary Project Management Plan*. PLN-2489; INL/EXT-05-00952. Idaho Falls, ID: Idaho National Laboratory.Longnecker and Associates. 2012.

[2] *Transactions of the American Nuclear Society* 117(October 2017):225–228, Washington, DC.

Nuclear Power 2010 Program: Combined Construction and Operating License & Design Certification Demonstration Projects Lessons Learned Report. Washington, DC: Department of Energy

D

The Current Role of Government in Demonstrations, with a Focus on the Department of Energy

A key Department of Energy (DOE) mission is to support the development of advanced energy technologies that address major energy challenges, such as bringing to market low-carbon alternatives. As Appendix C discussed, one key example of this for nuclear energy was the NP2010 program that resulted in the design and certification of the AP1000 and ESBWR (National Research Council 2008). The Gen IV Roadmap (U.S. DOE Nuclear Energy Research Advisory Committee and Gen IV International Forum 2002) also sparked concepts of small modular reactor (SMR) designs for many of the advanced reactors that are now being supported by DOE. This section reviews the current role of government in reactor demonstrations.

SMALL MODULAR REACTOR TECHNOLOGY AWARD AND CARBON-FREE POWER PROJECT AWARD

The first of the DOE programs in support of SMR technology development focused on LWR technology (DOE 2023a). In 2013, NuScale Power was selected as the winner of the DOE competitively bid, $226 million, 5-year, financial assistance award to develop this SMR LWR technology. In 2015, DOE awarded $16.6 million to NuScale Power for the preparation of a combined Construction and Operating License Application (COLA) with its first customer, Utah Associated Municipal Power Systems' (UAMPS[1]) for the Carbon Free Power Project (CFPP) (DOE 2020a). UAMPS plans to site a NuScale reference plant in Idaho and is expected to be operational by the end of this decade.

In 2018, in a sign of continued support, DOE awarded NuScale $40 million in cost-sharing financial assistance under its "U.S. Industry Opportunities for Advanced Nuclear Technology Development" funding opportunity. This federal R&D award objective is to support industry's acceleration of these technologies to promote U.S. energy independence, energy dominance, electricity grid resiliency, national security, and clean baseload power. Since 2013, DOE has provided more than $600 million in cost-share awards for development (NuScale 2023b). This has resulted in a complete NuScale standard plant design that was approved by the U.S. Nuclear Regulatory Commission in 2020 and certified in 2023.

Utah Associated Municipal Power Systems formally launched the CFPP in 2015. In 2016, DOE issued a Site Use Permit to UAMPS for the CFPP, which permitted UAMPS to identify and characterize potential locations for licensing and constructing a NuScale plant within the 890-square mile Idaho National Laboratory (INL) in Idaho Falls. The preferred INL site was selected in July 2019. In October 2020, DOE approved a $1.355 billion multi-year cost-share award to CFPP LLC, a single-purpose, non-

[1] UAMPS is a subdivision of the State of Utah that provides wholesale electric-energy, transmission, and other energy services, on a non-profit basis, to community-owned power systems throughout the Intermountain West. Its 50 members include public power utilities in seven states: Utah, Arizona, California, Idaho, Nevada, New Mexico, and Wyoming.

profit organization wholly owned by UAMPS, to cost-share the development and construction of the CFPP.

In January 2021, UAMPS and NuScale executed agreements to help manage and derisk the development of the CFPP. Based on initial orders from UAMPS, Fluor Corporation and NuScale are to develop more precise cost estimates and initial project planning work for the licensing, manufacturing, and construction of the CFPP. On March 9, 2023, NuScale announced that it had signed a contract with Doosan Enerbility to order long lead materials for six upper Reactor Pressure Vessels. The order includes heavy forgings, steam generator tubes, and weld materials (NuScale 2023a).

ADVANCED REACTOR TECHNOLOGY R&D PROGRAM

Currently, DOE has a dual track approach to the development of advanced non-LWR reactors. This dual track approach is a result of ongoing DOE advanced reactor programs and a new initiative mandated by Congress in the 2020 Appropriations Act (U.S. Congress 2020), so-called Advanced Reactor Demonstration Program (ARDP) (DOE 2023b). Based on this approach, it appears that any future advanced reactor R&D program will need to fit within, or emerge from, this DOE organization.

Through a collection of individual efforts, DOE supports private companies to develop and demonstrate small modular non-LWR advanced reactors—that is, beyond current GWe-scale light water reactors (LWRs). These efforts include:

- An Advanced Reactor Demonstration Program (ARDP) has three parts (DOE 2020b). The first part provides for DOE to demonstrate two Advanced Reactors. Based on an industry solicitation, DOE has chosen two Small Modular Reactors (SMRs) for reactor demonstration. One SMR is a fast spectrum sodium-cooled design (345 MWe) under development by Terrapower and GE-Hitachi (TerraPower 2020). The other SMR is a thermal spectrum gas-cooled design (80 MWe) under development by X-Energy (X-energy 2023). Both demonstration projects are currently planned to be functional by the end of the decade (DOE 2020c). This is an extremely aggressive schedule, which many judge to be unrealistic. This program considers these reactor designs to be technically mature enough from past R&D accomplishments that there is little need for additional R&D. These plant designs are to proceed directly to demonstration. The implicit assumption is that (1) the technology base is adequate to complete the design, license, build and operate; and (2) that the plants will demonstrate that these advanced designs can be competitive with LWRs. The eventual demonstration of these two advanced reactors would establish the cost of each FOAK plant and provide companies with the information necessary to bring their cost into a range that will be competitive.
- The second part of the ARDP program provides funds for “Risk Reduction” for five industry teams. Each team is expected to address key aspects of their design that require R&D to reduce the technical and regulatory risks for their design. The goal of the Risk Reduction program is to design and develop safe and affordable reactor technologies that can be licensed and deployed by 2035 (DOE 2020d).
- The third part, “Advanced Reactor Concepts—20” (ARC-20), funded through the Advanced Reactor Technologies (ART) program, provides support for three teams in order to assist the progression of advanced reactor designs in their earliest phases of their design concept. The goal of this program is to help solidify these design concepts toward a mature technology for potential demonstration after the mid-2030s (DOE 2020e).

Taken together, DOE is now funding a large development and demonstration program that is meant to provide eventual demonstrations of at least two and possibly more of these diverse advanced reactors designs. Over the course of the ARDP program, DOE would need to invest almost $4 billion[2] ($220 million in 2021[3]), subject to the availability of future congressional appropriations. Industry teams would provide matching funds for the two demonstrations. ARC-20 projects are not a 50-50 cost share.

The second approach is the ongoing R&D program managed by DOE and funded through annual appropriations to the Office Nuclear Energy. It focuses on more basic applied technology reactor development. As described in DOE Budget documents the broad program is:

- The Advanced Small Modular Reactor subprogram: This program has an emphasis on cost-shared R&D. These research activities focus on cross-cutting engineering technologies that are relevant to a broad spectrum of advanced small modular reactor designs, while minimizing potential duplication of effort with the Advanced Reactors Technologies subprogram.
- The Advanced Reactors Technologies subprogram: This program focuses on research for long-term reactor concepts. It also emphasizes early-stage R&D needs of promising mid-range concepts as well as development of innovative technologies that benefit multiple advanced reactor concepts. This specifically includes emerging microreactor design concepts, as well as stimulation of new ideas for transformational engineering concepts.[4] As discussed later, this does not seem to be coordinated with the transformational research objectives organized and funded by the ARPA-E.

These are DOE base technology R&D programs and they do not have any schedule requirements that are an integral part of the ARDP congressionally mandated demonstration programs.

VERSATILE TEST REACTOR AT IDAHO NATIONAL LABORATORY

There is an ongoing need to provide national R&D test beds in support of advanced reactor research and development. These test beds involve cutting-edge experimental capabilities, computational capabilities, and databases, and staffing those activities with qualified people. Current experimental test beds include the Advanced Test Reactor (ATR), the Transient Reactor Test Facility (TREAT), and the High Flux Isotope Reactor (HFIR), and require appropriate federal and industry support to maintain their capabilities.

The Versatile Test Reactor (VTR) is a fast-spectrum neutron source that can add to the suite of U.S. nuclear technology test beds to provide needed data for technology developers and scientists from all over the nation (INL 2023). The VTR objective is to reestablish U.S. global leadership in nuclear energy R&D, while attracting potential collaborations, investments, and personnel from international research partners. The fast-neutron Versatile Test Reactor was planned to be constructed by 2030 to accelerate testing of advanced nuclear fuels, materials, and components. DOE launched the Versatile Test Reactor Program following studies that analyzed the need for a research reactor that could test materials, fuels and other components at higher neutron energies and neutron fluxes than what is available today. Several advanced reactor developers have voiced support for a fast neutron irradiation capability in the United States to enable next-generation technology development. An INL-led team (including ANL, LANL, ORNL, PNNL and SRNL and universities and industry) was collaborating on the program.

In fiscal year 2018, Congress allocated $35 million to the DOE Office of Nuclear Energy to explore what it would take to build a fast spectrum test reactor to support advanced nuclear reactor research and development in the United States. Subsequently, $65 million was set aside in FY 2019. In

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[2] ARDP program total funding about $3.2 billion for Demo projects, $600 million for Risk Reduction and $50 million for ARC-20.

[3] Note: An additional $30 million was provided for Regulatory Development, Advanced Reactor Safeguards and National Reactor Innovation Center.

[4] Department of Energy, 2021, "Congressional Budget Justification," vol. 3, part 2, p. 34.

February 2019, VTR cleared Critical Decision 0, the first in a series of project approvals required by DOE Order 413.3B. To pass CD-0, a project must demonstrate that a mission need requiring investment exists such as meeting a scientific goal or establishing a new research capability. For FY 2020 and FY 2021, the project received $90 million to complete the analysis of alternatives, the conceptual design of the preferred alternative and a specific cost/schedule estimate. Detailed cost estimates are not yet publicly available. NE subsequently received approval for Critical Decision CD-1, Approve Alternative Selection and Cost Range in September 2020. Other significant project milestones included the December 2020 Secretarial approval, with concurrence through the Under Secretary for Nuclear Security Administration and the Assistant Secretary for Nuclear Energy, to use a uranium/plutonium/zirconium metal alloy driver fuel and the publication of the VTR Environmental Impact Statement and Record of Decision in 2022. Congress did not fund the VTR project in FY 2022 or FY 2023. The project is in standby status.

Timely decisions are needed to move the project forward or to transition to another approach to obtain the needed R&D capabilities.

ARPA-E PROGRAMS IN SUPPORT OF NUCLEAR ENERGY

The Advanced Research Projects Agency-Energy (ARPA-E) is an agency within the Department of Energy. It was created in 2007 by the America COMPETES Act and is modeled after DARPA in the Department of Defense. Its focus is to advance high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E programs support energy projects that can be substantively advanced with a small amount of funding ($2 million–$10 million) over a defined period of time (2–3 years). The ARPA-E program opportunities are normally focused on a particular energy specific topical area. Any one ARPA-E topical area aims to promote innovation in engineering science that then leads to an increased technical readiness for the targeted application (TRLs 3–5—beyond basic science but before a pilot project). Each ARPA-E program topic centers on a particular question, with the objective being to remove what is seen as a key barrier in an area that would not be addressed otherwise (or addressed with less focus). All ARPA-E projects have a custom technology to market component.

There are currently two major programs in nuclear energy, Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration (MEITNER) (ARPA-E 2018) and Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA) (ARPA-E 2020). The MEITNER program was created to develop innovative technologies that can enable advanced reactor designs for lower cost and safer operation. These enabling technologies could establish the basis for a modern, domestic supply chain supporting nuclear technology. The MEITNER program encourages a rethinking of how systems of the nuclear plant fit together when developing the technologies that will make these plants safer, cost competitive and technically viable. In addition, specific projects may be improved and validated using advanced modeling and simulation tools. ARPA-E also provided a Resource Team to help coordinate team activities for modeling and simulation, techno-economic analysis, and subject matter expertise. The MEITNER program began in summer of 2018 and made 10 awards totaling $24 million.

The GEMINA program seeks to develop digital twin (DT) technology for advanced nuclear reactors and transform operations and maintenance (O&M) systems for advanced nuclear plants. The goal is for interdisciplinary teams to design tools that introduce greater flexibility in reactor systems, increased autonomy in operations, and faster design iteration, with a goal is to enact a 10-times reduction in O&M costs for advanced reactor plants, thereby improving their economic competitiveness. Teams are expected to apply diverse technologies that are driving efficiencies in other industries, such as artificial intelligence (AI), advanced control systems, predictive maintenance, and model-based fault detection. Because advanced reactors are still in design phase, teams will develop surrogate systems that simulate advanced reactor core operating dynamics using both non-nuclear test facilities and digital twin simulations. They will use these systems to test their DT platforms. The GEMINA program began in summer of 2019 and made 10 awards totaling $27 million.

In May 2021, ARPA-E announced a new research funding opportunity, ONWARDS, of $40 million to reduce the disposal impact of spent fuel waste from advanced nuclear reactors (ARPA-E 2023a). In 2022, the CURIE program was announced to provide $48 million in competitive funding in support of reprocessing research and development (ARPA-E 2023b).

REFERENCES

Abdulla, A, M Ford, M G Morgan, and D G Victor. 2017. "A Retrospective Analysis of Funding and Focus in US Advanced Fission Innovation." *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/aa7f10.

ARPA-E. 2018. "Department of Energy Announces 10 Projects to Support Advanced Nuclear Reactor Power Plants: ARPA-E provides up to $24 million for technologies to enable lower cost, safer advanced nuclear plant designs." https://arpa-e.energy.gov/news-and-media/press-releases/department-energy-announces-10-projects-support-advanced-nuclear.

ARPA-E. 2020. "DOE Announces $27 Million for Advanced Nuclear Reactor Systems Operational Technology." https://arpa-e.energy.gov/news-and-media/press-releases/doe-announces-27-million-advanced-nuclear-reactor-systems-operational.

ARPA-E. 2023a. "Optimizing Nuclear Waste and Advanced Reactor Disposal Systems." https://arpa-e.energy.gov/technologies/programs/onwards.

ARPA-E. 2023b. "Converting UNF Radioisotopes into Energy." https://arpa-e.energy.gov/technologies/programs/curie.

U.S. Congress. 2020. Energy and Water Development Appropriations Bill, 2020. edited by U.S. Senate. https://www.congress.gov/116/crpt/srpt102/CRPT-116srpt102.pdf.

DOE (Department of Energy). 2020a. "DOE Approves Award for Carbon Free Power Project." https://www.energy.gov/ne/articles/doe-approves-award-carbon-free-power-project.

DOE. 2020b. "INFOGRAPHIC: Advanced Reactor Development." https://www.energy.gov/ne/articles/infographic-advanced-reactor-development.

DOE. 2020c. "U.S. Department of Energy Announces $160 Million in First Awards Under Advanced Reactor Demonstration Program." https://www.energy.gov/ne/articles/us-department-energy-announces-160-million-first-awards-under-advanced-reactor.

DOE. 2020d. "Energy Department's Advanced Reactor Demonstration Program Awards $30 Million in Initial Funding for Risk Reduction Projects." https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-30-million-initial.

DOE. 2020e. "Energy Department's Advanced Reactor Demonstration Program Awards $20 million for Advanced Reactor Concepts." https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-20-million-advanced.

DOE. 2023a. "Advanced Small Modular Reactors (SMRs)." https://www.energy.gov/ne/advanced-small-modular-reactors-smrs.

DOE. 2023b. "Advanced Reactors Demonstration Program." https://www.energy.gov/ne/advanced-reactor-demonstration-program.

U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum 2002. "A Technology Roadmap for Generation IV Nuclear Energy Systems." https://www.gen-4.org/gif/jcms/c_40481/technology-roadmap

INL (Idaho National Laboratory). 2023. "Frequently Asked Questions." https://inl.gov/trending-topic/microreactors/frequently-asked-questions-microreactors.

NuScale. 2023a. "NuScale Power Places First Long Lead Material Production Order with Doosan Enerbility." https://www.nuscalepower.com/en/news/press-releases/2023/nuscale-power-places-first-long-lead-material-production-order-with-doosan-enerbility.

NuScale Power Corporation. 2023b. "United States Securities and Exchange Commissions: Form 10-K." https://cdn.kscope.io/af84ea51623f5e8497c0f94e6d140219.html.

TerraPower. 2020. "TerraPower and GE Hitachi Nuclear Energy Introduce Commercial Natrium™ Power Production and Storage System." https://www.terrapower.com/terrapower-and-ge-hitachi-nuclear-energy-launch-natrium-technology.
X-energy. 2023. "X-energy's Reactor: Xe-100: The safest, most economic and most advanced design for a small modular nuclear reactor." https://x-energy.com/reactors/xe-100.

E

Nuclear Cooperation Agreement Details

There are nine requirements for nuclear cooperation agreements (NCAs), with additional conditions, tailored in specifics through negotiations (see Table E-1). The Department of State leads NCA negotiations under the interagency guidance of the National Security Council, with assistance and concurrence of the Department of Energy and in consultation with the U.S. Nuclear Regulatory Commission. The President shares any proposed agreement for consultation to the House Committee on Foreign Affairs and the Senate Committee on Foreign Relations along with an unclassified Nuclear Proliferation Assessment Statement (NPAS) with a classified annex, which then goes to Congress as a whole, and the agreement goes into effect unless Congress issues a Joint Resolution of disapproval (CRS 2021; GAO 2020). The length of time for the negotiations among the parties to the agreement varies considerably, as they depend on the availability of the negotiating resources and the levels of interest. They average 400 days from an initial memorandum to entry into force up to a decade or more for agreements with new partners. The NCA Agreements, referred to in the United States as "123 Agreements," typically have a time limit, requiring renegotiation for extension and the cooperating parties have a safeguards agreement with the IAEA and are parties to the Additional Protocol for the Convention on Physical Protection of Nuclear Materials (CPPNM/AP). Pursuant to the 123 Agreement, the United States also negotiates "subsequent arrangements" on implementing the agreement, such as duration or physical protection requirements, and can cover any other arrangement for nonproliferation purposes (CRS 2021).

TABLE E-1 The Nine Conditions for 123 Agreements

	The Nine Conditions for 123 Agreements
1	IAEA Comprehensive Safeguards for Non-Nuclear Weapons States
2	Other Agreement-Specific Safeguards as Agreed by the Parties
3	Guarantee of Peaceful Use by the Cooperating Party (including use for research for any military purpose)
4	Right to Require Return from Non-Nuclear Weapons States of Transferred Items (Including material produced through such items)
5	Physical Security Guarantee by the Cooperating Party
6	Retransfers Require U.S. Consent
7	No Enrichment or Reprocessing Activities without U.S. Consent
8	Storage Facilities for Transferred Nuclear Materials Require U.S. Advance Approval
9	Additional Restrictions

SOURCE: J. Warden, 2021, "U.S. Agreements for Peaceful Nuclear Cooperation (123 Agreements)," presented to the committee on October 4, 2021. Available by request through PARO@nas.edu.

Under the "Additional Restrictions" condition, in its 123 Agreement with the United Arab Emirates the United States developed a "gold standard" where the cooperating party applies all the conditions, including no enrichment or reprocessing without U.S. consent, to any special nuclear materials or nuclear facilities under its jurisdiction, whether they stem from the items transferred under the 123 Agreement or not. The United States has sought similar commitments in its subsequent 123 Agreement negotiations, along with the requirement for adopting the Additional Protocol, which has proved difficult in some negotiations (GAO 2020). However, the negotiations elaborate how the parties will meet the nine conditions, including the gold standard, which allows the Department of State to seek palatable alternatives that not only achieve the nonproliferation and national security aims of the conditions, but address U.S. geostrategic objectives of nuclear cooperation. For example, the Agreements with the UAE and Taiwan contain legally binding commitments against enrichment activities, while the Agreements with Mexico and Vietnam contain political commitments to obtain fuel only from the international market, thus forsaking enrichment activities.

The Department of State perceives the 123 Agreements as having an agnostic perspective on their application to new and advanced reactors and their related technologies (Warden 2021). Nonetheless, the conditions may prove more problematic for some reactor types, such as U. S. consent for enriching fuels for any reactors in their jurisdiction requiring HALEU, and to negotiations involving any of the more than sixty countries yet to ratify the Additional Protocol (IAEA 2022). The gold standard and other 123 Agreement conditions have prompted some to suggest reforming the agreements to rely more on greater inspector access and better tools and practices for verification and monitoring and viewing favorably "black box" or "design, build, operate," particular for transfers of new and advanced civilian nuclear power reactors (Nephew 2020).

REFERENCES

CRS (Congressional Research Service). 2021. *Nuclear Cooperation with Other Countries: A Primer*. RS22937. Washington, D.C: Congressional Research Service.

GAO (Government Accountability Office). 2020. *U.S.-Saudi Nuclear Cooperation: Progress Is Stalled Over Nonproliferation Conditions and Agency Management of Negotiations Is Unclear*." GAO-20-343. https://www.gao.gov/products/gao-20-343#:~:text=GAO%2D20%2D343%20Published%3A,and%20equipment%20from%20the%20U.S.

IAEA (International Atomic Energy Agency). 2022. "Status List, Conclusion of Additional Protocols." https://www.iaea.org/sites/default/files/20/01/sg-ap-status.pdf.

Nephew, R. 2020. *Reconsidering U.S. Nuclear Cooperation Agreements*. CGEP Report 032320. New York: Columbia University, Center on Global Energy Policy. https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/NucCoopAgreements_CGEP-Report_032420.pdf.

Warden, J. 2021. "U.S. Agreements for Peaceful Nuclear Cooperation (123 Agreements)." Briefing to the Committee on October 4, 2021.

F

Acronyms and Abbreviations

AI	artificial intelligence
AMO	Advanced Manufacturing Office
ANS	American Nuclear Society
ARDP	Advanced Reactor Demonstration Program
ARPA-E	Advanced Research Projects Agency–Energy
ASME	American Society of Mechanical Engineers
BTO	Building Technologies Office
BWR	boiling water reactor
CCF	common cause failure
CCUS	carbon capture, utilization, or sequestration
COL	Combined Operating License
DC	Design Certification
DoD	Department of Defense
DOE	Department of Energy
DOE-NE	Department of Energy Office of Nuclear Energy
DSO	distribution system operator
EBR-II	Experimental Breeder Reactor II
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
EPZ	emergency planning zone
EXIM	export-import bank
FDR	final design review
FERC	Federal Energy Regulatory Commission
FHR	fluoride-molten-salt-cooled high-temperature reactor
Flibe	lithium-fluoride, beryllium fluoride molten salt
FOAK	first-of-a-kind
GAIN	Gateway for Accelerated Innovation in Nuclear
GHG	greenhouse gases
GFR	gas-cooled fast reactor
HALEU	high-assay low-enrichment uranium

HTGR	high-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
ISO	Independent System Operator
LCOE	levelized cost of energy
LPO	Loan Program Office
LWR	light water reactor
ML	machine learning
MOPR	Minimum Offer Price Rule
MOU	memorandum of understanding
MSR	molten-salt-fuel-cooled reactor
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Initiative
NOAK	nth-of-a-kind
NPM	Nuclear Power Module
NPP	nuclear power plant
NQA-1	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NRIC	National Reactor Innovation Center
NSUF	Nuclear Science User Facilities
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
PCU	power conversion unit
PNNL	Pacific Northwest National Laboratory
PPA	Power Purchase Agreement
PWR	pressurized water reactor
QA	quality assurance
R&D	research and development
ROW	rest of the world
RTO	Regional Transmission Operator
SFR	sodium fast reactor
SMR	small modular reactor
TRISO UCO	tri-structural isotropic fuel of uranium-oxycarbide
TSO	transmission system operator
UC	uranium-carbide
UCl	uranium-chloride

UF	uranium-fluoride
UN	uranium-nitride
UO_2	uranium-dioxide
VPP	virtual power plant
WNA	World Nuclear Association

G

Committee Member Biographical Information

Richard A. Meserve, *Chair*, is Senior of Counsel in the Washington, DC, office of Covington & Burling LLP, president emeritus of the Carnegie Institution for Science, and former chair of the U.S. Nuclear Regulatory Commission. Early in his career, after obtaining a PhD in applied physics from Stanford University and a JD from Harvard Law School, Dr. Meserve served as law clerk to Supreme Court Justice Harry A. Blackmun and as legal counsel to the president's science advisor. He has served on and chaired numerous legal and scientific committees, including many convened by the National Academies. Among other activities, he is the former president of the board of overseers of Harvard University and chair of the International Nuclear Safety Group (chartered by the International Atomic Energy Agency). Dr. Meserve is on the board of the Kavli Foundation and chair of the board of the Health Effects Institute. He is a member of the National Academy of Engineering and served on its council. He is also a member of the American Academy of Arts and Sciences (former member of its council and trust), the American Philosophical Society, and the Council on Foreign Relations, a fellow the American Physical Society, and a foreign member of the Russian Academy of Sciences.

Ahmed Abdulla is an assistant professor in the Department of Mechanical and Aerospace Engineering at Carleton University, where he co-leads the APEX (Alternative Pathways for the Energy Transition) research group. An energy engineer, Dr. Abdulla develops energy system models for deep decarbonization that faithfully integrate techno-economic risks, behavioral science, and public policy to deploy technologies sustainably, ensuring viability both techno-economically and socio-politically. Modeling efforts focus on evaluating the role of disruptive energy technologies that sit at a low level of technical readiness, including energy storage systems, advanced nuclear power, and negative emissions technologies. His research advances technology process modeling, systems engineering, and quantitative risk and decision analysis. Prior to Carleton, Dr. Abdulla was an assistant research professor at Carnegie Mellon University and an assistant research scientist at the University of California San Diego. He received his BSE in chemical engineering from Princeton University, and his PhD in engineering and public policy from Carnegie Mellon University.

Todd Allen is currently a faculty member and chair of the Nuclear Engineering and Radiological Sciences Department at the University of Michigan and a senior fellow at Third Way, a DC-based think tank, supporting their clean energy portfolio. Dr. Allen was the Deputy Director for Science and Technology at the Idaho National Laboratory from January 2013 through January 2016. Both the INL and Third Way positions occurred while on leave from the University of Wisconsin. Previously, he was a professor in the Engineering Physics Department at the University of Wisconsin, a position held from September 2003 through December 2018. In addition to his teaching and research responsibilities at Wisconsin, he was also the Scientific Director of the Advanced Test Reactor National Scientific User Facility, centered in Idaho Falls, Idaho, at the Idaho National Laboratory. He held that position from March 2008 to December 2012. He was also the Director of the Center for Material Science of Nuclear Fuel, a Department of Energy-sponsored Energy Frontier Research Center. Prior to joining the faculty at the University of Wisconsin, he was a Nuclear Engineer at Argonne National Laboratory-West in Idaho

Falls. His doctoral degree is in Nuclear Engineering from the University of Michigan (1997). Prior to graduate work, he was an officer in the U.S. Navy Nuclear Power Program.

Jaquelin Cochran is the director of the Grid Planning and Analysis Center at the National Renewable Energy Laboratory, where she has worked since 2009. Dr. Cochran's work has focused on the evolution of the power grid with high deployment of renewable energy. She recently led the Los Angeles 100% Renewable Energy Study and a portfolio of analyses about India's power system. Before joining NREL, Dr. Cochran was an Assistant Professor of Natural Resource Management with KIMEP University in Almaty, Kazakhstan. She also served as a Peace Corps Volunteer for two years with the Polish Foundation for Energy Efficiency (FEWE) in Krakow. She holds a PhD and MA from the Energy and Resources Group at the University of California at Berkeley, and a BA from Pomona College.

Michael L. Corradini is Emeritus Wisconsin Distinguished Professor of Nuclear Engineering and Engineering Physics at the University of Wisconsin-Madison. Dr. Corradini served from 1995 to 2001 as associate dean for the College of Engineering and as Chair of Engineering Physics from 2001 to 2011. He has published widely in areas related to vapor explosion phenomena, jet spray dynamics, and transport phenomena in multiphase systems. From 1978 to 1981, he served as a member of technical staff of Sandia National Laboratories. In 1998, he was elected to the National Academy of Engineering. He has also served as a presidential appointee in 2002 and 2003 as the chairman of the Nuclear Waste Technical Review Board (a separate government agency). From 2004 to 2008, he served as a board member of the INPO National Accreditation Board for Nuclear Training. In 2006, he was appointed to the NRC Advisory Committee on Reactor Safeguards and was elected to the National Council on Radiation Protection. In 2010, he was appointed chair of the Scientific Advisory Committee to the French Atomic Energy Agency. He began and served as the director of the Wisconsin Energy Institute. He was elected as the President of the American Nuclear Society (2012–2013). Dr. Corradini received his BS in mechanical engineering from Marquette University, Milwaukee; MS in nuclear engineering from Massachusetts Institute of Technology; and PhD in nuclear engineering from Massachusetts Institute of Technology.

Richard Cupitt is a senior fellow and director of the Partnerships in Proliferation Prevention program at Stimson. Dr. Cupitt's areas of expertise include WMD nonproliferation, export controls, and foreign policy. Prior to joining Stimson, he served as the Special Coordinator for U.N. Security Council resolution 1540 in the Office of Counterproliferation Initiatives at the U.S. State Department from 2012 through 2016. As such, he led U.S. government efforts to further implementation of the more than two hundred legally binding obligations and recommendations of the resolution, which aims to combat proliferation of WMD and their means of delivery, especially to non-state actors such as terrorists and criminal organizations. From 2005 to 2012, Dr. Cupitt worked as an expert for the committee established pursuant to U.N. Security Council resolution 1540 (2004), a subsidiary body of the U.N. Security Council, monitoring and facilitating implementation of the resolution in all U.N. Member States, along with building relationships with more than forty international organizations, coordinating assistance activities, and conducting outreach with industry and academia. Elected coordinator of the experts from 2010–2012, he also led the work in several specialized areas including combating the financing of proliferation and export controls. From 2004 to 2008, Dr. Cupitt also held a position as Scholar-in-Residence at American University and worked as Special Adviser for International Cooperation for the U.S. Undersecretary of Commerce in the Bureau of Industry and Security (2002–2004). From 1988 to 2002, Dr. Cupitt had various posts for the Center International Trade and Security (CITS) of the University of Georgia, including associate director, as well as acting as a visiting scholar at the Center for Strategic and International Studies (CSIS) (2000–2002). Dr. Cupitt also has held academic positions at Emory University and the University of North Texas. He has produced four books and more than 20 peer-reviewed articles on nonproliferation export controls, along with dozens of other security or trade-oriented publications. In addition, he has served as a consultant on projects for the U.S. State Department, several U.S. national commissions, U.S. national nuclear laboratories, and various international organizations.

Leslie Dewan is the CEO of RadiantNano, a nuclear startup developing next-generation radiation detectors with applications in national security, clean energy production, and medical diagnostics. From 2011 to 2018, Dr. Dewan was the CEO of Transatomic Power, a company that designed safer nuclear reactors that leave behind less waste than conventional designs. Dr. Dewan received her PhD in nuclear engineering from MIT, with a research focus on computational nuclear materials. She also holds SB degrees from MIT in mechanical engineering and nuclear engineering. Before starting her PhD, she worked for a robotics company in Cambridge, MA, where she designed search-and-rescue robots and equipment for in-field identification of chemical and nuclear weapons. Dr. Dewan has been awarded an MIT Presidential Fellowship and a Department of Energy Computational Science Graduate Fellowship. She has served on the MIT Corporation, MIT's board of trustees. She was named a *TIME Magazine* "30 People Under 30 Changing the World," an *MIT Technology Review* "Innovator Under 35," a *Forbes* "30 Under 30," a *National Geographic* Explorer, and a World Economic Forum Young Global Leader.

Heather Feldman is the Director of Innovation in the Nuclear Sector at the Electric Power Research Institute (EPRI). Dr. Feldman leads a team that conducts applied R&D to overcome barriers for modernizing and maximizing the utilization of the existing nuclear fleet and for deploying advanced reactors. She is also leading EPRI's initiative on Artificial Intelligence. She serves on the Idaho National Laboratory Nuclear Science and Technology Strategic Advisory Committee, as well as the Board of Directors for E4 Carolinas. Prior to her current role, Dr. Feldman was the Director of Plant Support and led an expert team who develop new or enhanced technologies and processes for inspection and repair, aging management and flexible operations of nuclear power plants. She previously led and managed the Engineering Programs area and worked in the Steam Generator Management Program and the Office of Innovation. Before joining EPRI, Dr. Feldman worked for United Space Alliance, where she coordinated systems engineering and integration work in the thermal area of the Space Shuttle Program. Her work contributed to the successful Return-to-Flight mission after the Columbia accident. Dr. Feldman holds a bachelor of science, master of science, and a doctorate in mechanical engineering from Clemson University. She is currently pursuing a master of business administration from Wake Forest University.

Michael Ford is the associate laboratory director for engineering at the Princeton Plasma Physics Laboratory. In this role, Dr. Ford leads the pursuit of PPPL's mission to develop advanced fusion engineering knowledge and techniques and is responsible for all engineering support throughout the Laboratory. Prior to assuming his position at PPPL, Dr. Ford served as the strategy development director for the Energy and Global Security (EGS) Directorate at the Argonne National Laboratory. At Argonne, he helped develop strategies designed to build increased sponsor support for energy and national security related research. Dr. Ford remains active in energy, engineering risk, and environmental policy research, and led Phase I of the National Demonstration Reactor Siting Study supporting the National Reactor Innovation Center. Prior to his work in the National Laboratories system, Dr. Ford held research positions at the Harvard University Center for the Environment and at the Belfer Center for Science and International Affairs, Harvard Kennedy School. He earned his PhD in engineering and public policy at Carnegie Mellon University (CMU), where he conducted research in energy and the environment, with a focus on advanced reactor technology development and proliferation risk. Dr. Ford also served a full career as an officer in the U.S. Navy and held Navy subspecialties in nuclear engineering, resource management, and operations analysis. During his time on active duty, CAPT (Ret) Ford commanded the guided-missile cruiser USS BUNKER HILL (CG 52) and the guided-missile destroyer USS MUSTIN (DDG 89) and served as lead nuclear engineer (Reactor Officer) aboard USS NIMITZ (CVN 68). Ashore, he held senior finance and resource management positions on the U.S. Navy and U.S Joint Staffs at the Pentagon. In these positions, he developed standards for new warfare systems development and helped lead the Navy Quadrennial Defense Review process.

Kirsty Gogan is an internationally recognized leader in the design and deployment of scalable strategies to address global climate and energy needs. Co-founder and managing director of consulting firm, LucidCatalyst and climate-focused non-profit, TerraPraxis, Ms. Gogan's focus is on enabling high-impact rapid clean energy transitions for neglected parts of the decarbonization challenge; and defining, incubating, and initiating scalable strategies that fulfil the twin missions of prosperity and decarbonization. Through a combination of rigorous, credible analysis, relationships of trust, and values alignment with key influencers, LucidCatalyst and TerraPraxis map transformative solutions into the uncharted territory of decarbonization that are otherwise absent from the discourse. Kirsty is a sought-after advisor on science communication, climate change, competitiveness and innovation to governments, industry, academic networks and NGOs, including having previously worked at 10 Downing Street, and the Office of the Deputy Prime Minister. Ms. Gogan has served in various roles for the UK Government, including having led the national public consultation on nuclear new build sites for the UK, reviewed the UK national communications response to Fukushima, and provided editorial oversight for the revision of the Civil Nuclear Emergency Planning and Response Guidance. She is a regular contributor to climate-related initiatives at the International Atomic Energy Agency (IAEA), the OECD Nuclear Energy Agency (NEA) UNFCCC Conference of the Parties (COP) and the Clean Energy Ministerial (NICE Future Initiative). Ms. Gogan has co-authored multiple flagship reports, including *Missing Link to a Livable Climate: How Hydrogen Enabled Synthetic Fuels Can Help Deliver the Paris Goals* and the Energy Technologies Institute Nuclear Cost Drivers study as well as *Cost and Performance Requirements for Flexible Advanced Nuclear Plants in Future U.S. Power Markets*, commissioned by ARPA-E MEITNER.

Ning Kang is the Department Manager of the Idaho National Laboratory's Power and Energy Systems Department. Her research interests include clean and renewable energy resources grid integration, power systems reliability and resilience, and energy system decarbonization. Dr. Kang also serves as Department of Energy (DOE)'s Grid Modernization Laboratory Consortium's Pillar Lead for the Flexible Generation and Load area, one of the six pillars in DOE's Grid Modernization Initiative. Prior to joining INL, she was a Principal Engineer at the Argonne National Laboratory where she focused on research in transmission and distribution (T&D) systems co-simulation and planning and operations coordination, reliability impact of distributed energy resources (DERs) on the bulk electric system, advanced distribution management system (ADMS), and microgrid integration and impact analysis. Dr. Kang has had 6 years' industry R&D experience when she was a Senior R&D Engineer at ABB U.S. Corporate Research Center in Raleigh, NC. At ABB, she was the main contributor to developing a substation-based protection and automation solution for ABB's substation controllers, a Volt-VAR optimization solution considering high DER penetration for ABB's DMS software, and condition-based and data-driven algorithms for ABB's recloser controllers. She is the main creator of an open-source T&D systems co-simulation software (TDcoSim) and holds five U.S. patents and one U.S. patent application. She has co-authored more than 50 journal and conference papers, book chapters, and technical reports. Dr. Kang is a senior member of the IEEE Power and Energy Society. She is also the Reliability and Resilience Task Force Chair within the Idaho Strategic Energy Alliance under Idaho Governor's Office of Energy & Mineral Resources. Dr. Kang currently serves as the senior editor of the Power and Energy Section of the IEEE Access Journal and the advisory committee member and nuclear subcommittee member for POWERGEN International. Dr. Kang has been a registered Professional Engineer since 2015. She earned her doctorate in electrical engineering from the University of Kentucky.

Allison M. Macfarlane is currently professor and director, School of Public Policy and Global Affairs, Faculty of Arts, UBC. Dr. Macfarlane has held both academic and government positions in the field of energy and environmental policy, especially nuclear policy. Most recently, she directed the Institute for International Science and Technology Policy at The George Washington University. Dr. Macfarlane recently held a fellowship at the Wilson International Center for Scholars in Washington, DC, and was Fulbright Distinguished Chair in Applied Public Policy at Flinders University and Carnegie Mellon Adelaide in Australia. The first geologist (and the third woman) to chair the U.S. Nuclear Regulatory

Commission (2012–2014), Dr. Macfarlane holds a PhD in earth science from MIT and a BS from the University of Rochester. She has held fellowships at Radcliffe College, MIT, Stanford, and Harvard Universities, and has been on the faculty at Georgia Tech in Earth Science and International Affairs, at George Mason University in Environmental Science and Policy, and in the Elliott School of International Affairs at George Washington University. From 2010 to 2012, Dr. Macfarlane served on the White House Blue Ribbon Commission on America's Nuclear Future, created by the Obama Administration to recommend a new national policy on high-level nuclear waste. She has also served on National Academy of Sciences panels on nuclear energy and nuclear weapons issues. Dr. Macfarlane chaired the Science and Security Board of the *Bulletin of Atomic Scientists*, the group that sets the *Bulletin's* famous "doomsday clock." In 2006, MIT Press published a book she co-edited, *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*. Dr. Macfarlane has published extensively in *Science, Nature, Environmental Science and Technology*, the *Bulletin of the Atomic Scientists*, and other journals. Her research has focused on technical, social, and policy aspects of nuclear energy production and nuclear waste management and disposal as well as regulation, nuclear nonproliferation, and energy policy.

David Owens served as the executive vice president of Business Operations Group and Regulatory Affairs at Edison Electric Institute from October 1992 to June 2017. An executive with extensive experience in public policies concerning energy and utility operations, Mr. Owens is recognized as an industry expert on business transformation. After 36 years of service, he retired from the Edison Electric Institute, the association representing all U.S. investor-owned electric companies. Mr. Owens was the first African American to hold an officer title with the organization. He guided the association on issues affecting the future structure of the electric industry and the new rules in evolving competitive markets. Owens also spearheaded efforts to invest in the nation's electric infrastructure with new technology enhancing energy efficiency with smart buildings, smart meters, and smart grids. He served as chief engineer for the Division of Rates and Corporate Regulation with the Securities and Exchange Commission where he actively participated in landmark proceedings involving utility mergers, electric integration issues and utility financial disclosure. A driving force behind the founding of the American Association of Blacks in Energy, Mr. Owens has mentored generations of young men in careers in energy. He also served as a director of Xcel Energy Inc., from August 2017 until June 2021. On December 21, 2018, Mr. Owens was nominated to be an independent director of the Puerto Rico Electric Power Authority. He served as vice chair until August 2022. Mr. Owens is a recognized expert in the energy field and has been a leader in shaping constructive public policy frameworks to support the industry's transition to new and cleaner technologies. He served on boards of the National Academy of Sciences and chaired the National Institute of Standards and Technology Smart Grid Advisory Committee. Mr. Owens is a graduate of Howard University with bachelor's and master's of engineering degrees, as well as a master's degree in engineering administration from the George Washington University.

James A. Rispoli, a licensed professional engineer, is a professor of practice at the North Carolina State University. Mr. Rispoli served as a career senior executive in the Department of Energy, and while director of the Office of Engineering and Construction Management, was invited by the Secretary to forego career status to accept a Presidential appointment. Thus, he served as an Assistant Secretary of Energy from 2005 through 2008, nominated by the President and unanimously confirmed by the U.S. Senate. Rispoli previously completed 27 years of service in the U.S. Navy, retiring as a Captain, Civil Engineer Corps. Subsequently, he was managing principal for an ENR top tier engineering firm and regional president of another top tier engineering firm in Hawaii, where his practice included multi-disciplinary engineering, environmental planning and engineering, and construction management. Rispoli left the private sector to join the Department of Energy's new Office of Engineering and Construction Management in 1999. Articles and papers written by him on various subjects in engineering and leadership have been published, including seven published in either an edited book, or a refereed journal; and he has lectured extensively domestically and internationally in Japan, China, Singapore, Italy and the

United Kingdom. Rispoli serves on the Department of Energy's Environmental Management Advisory Board. He earned his BE degree in civil engineering from Manhattan College, an MS degree in civil engineering from the University of New Hampshire, and a master's degree in business from Central Michigan University. Rispoli is a Distinguished Member of the American Society of Civil Engineers (ASCE), a member of the National Academy of Construction (NAC), and a Board Certified Environmental Engineer (National Academy of Environmental Engineers and Scientists). He is a member of two permanent boards/committees of the National Academies of Sciences, Engineering and Medicine (NASEM), and is chair of one of them. Rispoli also recently served on a study committee of the National Academies' Nuclear and Radiation Studies Board. He developed and teaches two graduate engineering courses at the North Carolina State University in Raleigh, NC, and initiated a curriculum for a graduate engineering concentration in facilities engineering which the College of Engineering has since implemented.

Rachel Slaybaugh is currently a partner at DCVC. While serving on the committee, she was an associate professor of nuclear engineering at the University of California, Berkeley. Dr. Slaybaugh researched computational methods applied to nuclear reactors, nuclear non-proliferation and security, and shielding. She also served as a program director at the Department of Energy's ARPA-E. Dr. Slaybaugh was also a senior fellow at the Breakthrough Institute, was a faculty affiliate at the Berkeley Institute of Data Science, and served on several advisory committees. Her Rickover Fellowship took Dr. Slaybaugh to Bettis Atomic Power Laboratory before joining Berkeley. She received a BS in nuclear engineering from Penn State, where she served as a licensed nuclear reactor operator, and an MS and PhD from University of Wisconsin–Madison in nuclear engineering.

Sola Talabi is a principal with Pittsburgh Technical, which is a nuclear consulting firm that specializes in advanced reactor design and deployment. He is also an adjunct professor of nuclear engineering at the University of Pittsburgh and the University of Michigan. Dr. Talabi's experience includes design, numerical computational analysis, manufacturing, installation and testing of nuclear power plant components, and serving as risk manager at Westinghouse Electric Company, where he was responsible for risk awareness, assessment and response for advanced reactors including AP1000 and SMR. Dr. Talabi received the following degrees from Carnegie Mellon University: MBA, PhD (engineering and public policy) and MSc (mechanical engineering). He received his BSc in engineering from University of Pittsburgh. Dr. Talabi is also a certified risk manager.

Steven Zinkle is the Governor's Chair Professor for Nuclear Materials in the Nuclear Engineering and Materials Science and Engineering Departments at the University of Tennessee at Knoxville. Prior to joining the faculty at the University of Tennessee, Dr. Zinkle was chief scientist for Oak Ridge National Laboratory's (ORNL) Nuclear Science and Engineering Directorate and director of ORNL's Materials Science and Technology Division. He also served as director of ORNL's Metals and Ceramics Division, which merged into the Materials Science and Technology Division. Much of his research has utilized materials science to explore fundamental physical phenomena that are important for advanced nuclear energy applications, focusing on microstructure-property relationships. Dr. Zinkle's research interests include the investigation of deformation and fracture mechanisms in structural materials, physical metallurgy of structural materials, and the investigation of radiation effects in ceramics, fuel systems and metallic alloys for fusion and fission energy systems. He has written more than 300 peer-reviewed publications and is a member of the National Academies National Materials and Manufacturing Board. He is a fellow of seven professional societies including the American Nuclear Society (ANS), TMS (The Minerals, Metals & Materials Society), ASM International, the Materials Research Society, and the American Physical Society. Dr. Zinkle received a BS and MS in nuclear engineering, an MS in materials science, and a PhD in nuclear engineering, all from the University of Wisconsin at Madison.

H

Disclosure of Conflicts of Interest

The conflict of interest policy of the National Academies of Sciences, Engineering, and Medicine (http://www.nationalacademies.org/coi) prohibits the appointment of an individual to a committee authoring a Consensus Study Report if the individual has a conflict of interest that is relevant to the task to be performed. An exception to this prohibition is permitted if the National Academies determine that the conflict is unavoidable and the conflict is publicly disclosed. A determination of a conflict of interest for an individual is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

Heather Feldman has a conflict of interest in relation to her service on the committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States, because she is currently employed as Director of Nuclear Innovation at the Electric Power Research Institue (EPRI), which receives pooled funding from many utilities and vendor organizations, as well as small contributions from government agencies. EPRI is on multiple proposals for DOE's Advanced Reactor Demonstration Program. Some of the topics within Dr. Feldman's portfolio are in close alignment with this study's statement of task. The National Academies has concluded that in order for the committee to accomplish the tasks for which it was established, it must include a committee member with experience in electric power research. Dr. Feldman's career at EPRI speaks to her deep knowledge of the intersection of electricity and nuclear engineering. Having spent many years working on issues related to balance of plant, corrosion resistance, and non-destructive evaluation, she is an expert in operational issues that face the current fleet of nuclear power plants. In her current position, she is working with the existing fleet to modernize, adjust power output, and adapt operations to a rapidly changing electric grid. Her expertise in fleet modernization will be critical to inform the necessary attributes of future reactor systems, which is a key component of the study's task. The National Academies has determined that the experience and expertise of Dr. Feldman is needed for the committee to accomplish the task for which it has been established. The National Academies could not find another available individual with the equivalent expertise and breadth of experience who does not have a conflict of interest. Therefore, the National Academies has concluded that the conflict is unavoidable. The National Academies believes that Dr. Feldman can serve effectively as a member of the committee, and the committee can produce an objective report, taking into account the composition of the committee, the work to be performed, and the procedures to be followed in completing the study.

David Owens has a conflict of interest in relation to his service on the committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States because he currently serves as Director of the Board of Xcel Energy, a major shareholder owned utility that runs several nuclear power plants and has stake in future nuclear technology options. Mr. Owens sits on two committees as a board member: the Operations and Nuclear Committee, and the Finance Committee. Mr. Owens will be stepping down from his position at Xcel by May of 2021. The National Academies has concluded that in order for the committee to accomplish the tasks for which it was established, it must include a committee member with current and extensive experience in utility operations and strategy, and in electricity system regulations. As his biographical summary makes clear, Mr. Owens has extensive knowledge of the electricity industry and its stakeholders through his long career at the Edison Electric Institute, as well as a deep understanding of regulatory affairs related to electric utilities. His current work as a board member of Xcel Energy is testament to his expertise in both utility planning and nuclear operations. The National Academies has determined that the experience and expertise of Mr. Owens is needed for the committee to accomplish the task for which it has been established. The National Academies could not find another available individual with the equivalent expertise and breadth of experience who does not have a conflict of interest. Therefore, the National Academies has concluded that the conflict is unavoidable. The National Academies believes that Mr. Owens can serve effectively as a member of the committee, and the committee can produce an objective report, taking into account the composition of the committee, the work to be performed, and the procedures to be followed in completing the study.

I

Report Findings and Recommendations

CHAPTER 1

Finding 1-1**:** The energy system must undergo radical change at unprecedented speed to meet the existential challenge of climate change. Many technologies with a variety of different attributes can and will contribute to the evolution of the energy system, and the barriers to technologies that can contribute to a low-carbon future should be addressed and, if possible, overcome. Nuclear has the benefits of a small land footprint and reliable availability, but historically, it has had drawbacks related to high up-front development and capital costs and fuel-cycle associated risks.

Finding **1-2:** The earliest timeframe for U.S. commercialization of some advanced nuclear reactors will be in the mid-2030s, and only if the challenges identified in this report are addressed in this decade. Yet, the race against climate change is both a marathon and a sprint. Growth in electricity demand and the need to achieve economy-wide decarbonization over the coming several decades present important long-term opportunities for advanced nuclear technologies.

Finding 1-3**:** In order for advanced reactors to contribute significantly to a decarbonized energy system, there are many challenges that must be overcome. Their resolution requires sustained effort and robust financial support by the Congress, various departments of the U.S. government (especially the Department of Energy and the U.S. Nuclear Regulatory Commission), the nuclear industry, and the financial community. Given the urgency of the need to respond to climate change, it is important to seek the prompt resolution of issues associated with commercialization of low-carbon technologies.

CHAPTER 2

Finding 2-1**:** Many advanced reactor designs employ a combination of fuel, coolant, and moderator that result in a set of core components with potentially inherent favorable safety characteristics (e.g., physical stability, high heat capacity, negative reactivity feedbacks). The designs also include engineered passive safety systems that incorporate no active components (e.g., pumps, motor-activated valves) and could require no emergency AC power and fewer external operator actions. These inherent and engineered design attributes, if actualized, have the potential to make fulfilling key safety functions (i.e., reactivity control, heat removal, radioactivity containment) simpler, more reliable, more cost effective, and more tolerant of human errors. Employing sophisticated sensing and data collection could further improve safety by increasing component and systems reliability.

Finding 2-2**:** Reactor designers and owners must demonstrate that key safety functions (i.e., reactivity control, heat removal, radioactivity containment) are satisfied during normal operation, transients, and the full range of possible accidents. (The list of possible accidents considered for new and advanced reactor designs could be different from those considered for current light water reactors [LWRs].) This will require collection of integral test data at appropriate scales and operating experience, supplemented by supporting analyses. The safety risks associated with small and advanced reactors differ from those for conventional LWRs and require new testing facilities and demonstration facilities.

Recommendation 2-1: The Department of Energy should evaluate the need for common experimental facilities that would help provide the required testing to support licensing and long-term operations across multiple reactor concepts within a reactor class (e.g., gas-cooled or molten-salt-cooled concepts).

Finding 2-3**:** For all the non-light water reactors that require higher ^{235}U enrichment beyond current established levels, a new fuel supply chain system must be qualified and commercially developed. Without this fuel supply chain, widespread commercial deployment of these reactor concepts cannot be achieved. This high-assay low-enriched uranium, while one of many new supply chains that need to be established to support advanced reactors, is critical across many of the advanced concepts.

Finding 2-4**:** Advanced reactor concepts, while innovative in some aspects of their design, are generally based on relatively conventional fuels, materials, and manufacturing methods. Such conventional moderate-performance materials (e.g., currently code-qualified structural steels) are suitable for many non-demanding advanced reactor components, such as primary system piping. However, notable improvements in performance and economics could be achieved by more widespread use of better-performing materials for advanced fuels, high-performance fuel cladding materials, and advanced manufacturing (e.g., additive manufacturing). While many of the current concepts plan to move to commercial reactor demonstration with existing materials, optimization of future generations for further improvements in safety, reliability, and economics will require technology advancements.

Recommendation 2-2: The Department of Energy (DOE) should initiate a research program that sets aggressive goals for improving fuels and materials performance. This could take the form of a strategic partnership for research and development involving DOE's Office of Nuclear Energy and Office of Science, the U.S. Nuclear Regulatory Commission, the Electric Power Research Institute, the nuclear industry, national laboratories, and universities. The program should incentivize the use of modern materials science, including access to modern test reactors, to decrease the time to deployment of materials with improved performance and to accelerate the qualification (ASME Section III, Division 5 or equivalent) and understanding of life-limiting degradation processes of a limited number of high-performance structural materials—for example, reactor core materials and cladding.

Finding 2-5**:** The various advanced reactor systems are at different levels of technical maturity. Each reactor design concept requires the completion of certain key technology development activities. The time and effort needed depends, in part, on the technical readiness of the concept and prior operating experience with the specific reactor technology involved. More mature concepts, such as advanced small modular light water reactors, small modular sodium fast reactors, and small modular high-temperature gas-cooled reactors, might be technically ready for demonstration by the end of this decade. Less mature reactor concepts require a range of additional development activities before demonstration can occur (such as qualification of fuel or structural materials for prototypic conditions) and would not be ready for demonstration until after 2030. The success in getting concepts ready for regulatory review, building a demonstration plant in a timely and predictable manner, and proving operational excellence with demonstration plants will determine potential broader commercial deployment.

CHAPTER 3

Finding 3-1**:** Electrification owing to economy-wide decarbonization presents a significant market opportunity for advanced nuclear generation to serve the grid, particularly if its widespread commercial availability occurs when utilities are scaling up infrastructure to respond to this demand. Nuclear's competitiveness to serve this new demand is sensitive to cost projections. Models suggest that advanced nuclear will likely be competitive if sufficiently low costs are achieved (e.g., $2,000–$4,000/kW) regardless of other conditions. Advanced nuclear could also achieve significant growth at higher cost ranges (e.g., ~$4,000–$6,000/kW) if other power system costs are higher than expected (e.g., owing to limited transmission growth or limited materials) or there is growing demand for non-electricity products (e.g., hydrogen).

Finding 3-2**:** Grid reliability is paramount in an increasingly electrified economy, and a broad range of low-carbon technologies are currently available—or soon will be—to support reliability, both resource adequacy and operating reliability. On resource adequacy, advanced nuclear power can provide the high-value, low-carbon energy needed when wind, solar, and batteries are unavailable, but its overall economic competitiveness depends on the value of its (grid or non-grid) energy at other times of the year. Regarding operating reliability, advanced nuclear will be competing with many technology types—conventional and inverter-based—to offer grid services such as voltage and frequency stability. While the grid is not yet prepared to operate solely on inverter-based resources today, reliability solutions have the potential to evolve rapidly to match the growing deployment of inverters. These advancements, which could occur before commercial availability of advanced nuclear, could affect the market value for nuclear power to provide essential grid services.

Finding 3-3**:** At the moment, investors rarely focus on resilience in choosing among generators, except in highly constrained environments, because generators are relatively more resilient components of the grid. When it comes to enhancing power system resilience, utilities focus on the transmission and distribution system because they are more vulnerable to damage.

Recommendation 3-1: A forum similar to GridEX should be established by vendors, utilities, and industry support organizations, with the active participation of experts from the Departments of Energy and Homeland Security, to elaborate any additional risks that emerge owing to novel reactor deployment paradigms—such as placing reactors in industrial parks, underground, at sea, or in close proximity to multiple other modules, or controlling them remotely—and develop rules, guidelines, and standard operating procedures for reactor operators that ensure nuclear power's continued resilience and that seek to capitalize on the proposed versatility of advanced nuclear reactors.

Finding 3-4**:** Federal Energy Regulatory Commission Order 2222 opens the door for small and advanced reactors to have their output aggregated to serve evolving electricity markets. These reactors, if located on congested transmission nodes, could alleviate the need for new transmission.

Finding 3-5**:** Regional Transmission Operators (RTOs) want to integrate more low-carbon electricity generation resources. The Inflation Reduction Act adds/modifies various clean energy tax provisions in the Internal Revenue Code, which will expand the participation of clean energy technologies, including existing and advanced new nuclear, in wholesale, bulk power markets and retail electricity markets.

Recommendation 3-2: The Federal Energy Regulatory Commission (FERC) should continue to examine approaches to improve the Minimum Offer Price Rule (MOPR) to better value generation sources, like nuclear, that can provide resilience, reliability, and low-carbon benefits. FERC should conduct additional workshops and technical conferences to discuss the development of clearer rules

and price signals for clean generation and the capabilities provided by existing and evolving nuclear plants. In making changes to the MOPR, FERC should consider provisions in the Inflation Reduction Act that provide for existing nuclear to receive credits (Zero Emissions Nuclear Facilities Credit) for electricity produced after 2023 and before 2033 and consider legislation adopted in New York and Illinois that recognizes the value of existing nuclear. Last, FERC should consider the potential future impact of a broad range of new and expanded tax credits that apply to new nuclear, renewables, energy storage, hydrogen, and other clean energy technologies that serve electricity markets.

CHAPTER 4

Finding 4-1**:** The key economic challenge for advanced nuclear reactors is the need to either be cost competitive with other low-carbon energy systems in providing electricity, expand their use to applications beyond the electricity sector, or have an otherwise strong value proposition that encourages investment. Given anticipated market conditions, and the range of low carbon energy technology options, this will require reductions in capital cost.

Finding 4-2**:** Nuclear developers face higher financing costs, and thus a greater sunk cost burden, than developers of other energy technologies. These higher costs result from (1) uncertain development and build times and (2) limited financing options and high interest rates that increase the finance burden, partly a result of a poor track record and consistent cost overruns in past construction.

Finding 4-3**:** Commercialization of multiple designs would logically necessitate the development of a variety of supply chains. For example, there are multiple fuel types proposed for the competing advanced reactor designs. Extended operating cycles with fewer refueling outages may affect demand stability for nuclear fuel. Thus, fuel fabrication may exacerbate the cost challenges for nuclear power.

Finding 4-4**:** Diseconomies of scale exist in certain nuclear power development and deployment scenarios. The diseconomies of scale may be owing to increased complexity and addition of systems associated with increased plant size, as well as the need for robust supply chains to support additional complexity and size.

Recommendation 4-1: The Department of Energy should continue to support developers in their efforts to design smaller plants and microreactors. This may be an early and low-risk path for nuclear deployments in certain selected applications where reduced scale may enable better control of cost and schedule overruns, potentially creating demand-pull, a larger number of orders, and greater potential for rapid learning.

Finding 4-5**:** Past studies suggest that for advanced reactors to achieve a strong market demand signal, it is likely that they will need to reach overnight capital costs in the range of ~$4000–$5000/kWe. While final costs for planned Advanced Reactor Demonstration Program (ARDP) plants are still quite uncertain, the level of government funding and vendor matching contributions (for the first-of-a-kind [FOAK] demonstrations) implies a cost level of approximately 2–2.5 times the $4000–$5000/kWe cost threshold. Significant and rapid learning and cost reductions will be necessary when moving from FOAK to nth-of-a-kind (NOAK) cost levels.

Finding 4-6**:** The Department of Energy (DOE), Office of Nuclear Energy, and Office of Clean Energy Demonstration portfolios support national infrastructure, databases, and human resources; basic discovery research; concept development and improvement; and support for demonstrations. As a means of reducing risk against an uncertain future, the portfolio entertains a diversity of approaches and designs. At the same time, strong evaluation criteria are warranted for deciding on programmatic elements subject to careful consideration of realistic budget constraints. The current DOE portfolio is not structured to continuously move ideas from basic discovery to deployment and has not incorporated independent reviews of Advanced Reactor Demonstration Program (ARDP) project performance nor demonstrated the ability to make funding decisions based on accomplishment of critical development milestones. There is a risk that future funding instability and lack of rigorous oversight may result in a failure to achieve the program goal of demonstrating multiple nuclear technologies that can be commercialized.

Recommendation 4-2: The nuclear industry and the Department of Energy's Office of Nuclear Energy should fully develop a structured, ongoing program to ensure the best performing technologies move rapidly to and through demonstration as measured by technical (testing, reliability), financial (cost, schedule), regulatory, and social acceptance milestones. Concepts that do not meet their milestones in the ordinary course should no longer receive support and newer concepts should be allowed to enter the program in their place.

Recommendation 4-3: Congress and the Department of Energy (DOE) should maintain the Advanced Reactor Demonstration Program (ARDP) concept. DOE should develop a coordinated plan among owner/operators, industry vendors, and the DOE laboratories that supports needed development efforts. The ARDP plan needs to include long-range funding linked to staged milestones; ongoing design, cost, and schedule reviews; and siting and community acceptance reviews. This plan will help DOE downselect among concepts for continued support toward demonstration. A modification in the demonstration schedule that takes a phased (versus concurrent) approach to reactor demonstration may be required. For example, funding would be continued for the first two demonstrations under the ARDP. A second round of demonstrations of designs expected to mature from the current ARDP Risk Reduction for Future Demonstrations award recipients could be funded for demonstration under an "ARDP 2.0" starting thereafter and going into the future.

Recommendation 4-4: To enable a cost-competitive market environment for nuclear energy, federal and state governments should provide appropriately tailored financial incentives (extending and perhaps enhancing those provided recently in the Inflation Reduction Act) that industry can use as part of a commercialization plan, consistent with the successful incentives provided to renewables. These tools may vary by state, locality, and market type. Continued evaluation of the recently passed incentives will need assessment to determine their adequacy. The scale of these incentives needs to be sufficient not only to encourage nuclear projects but also the vendors and the supporting supply chains.

CHAPTER 5

Finding 5-1**:** In principle, nuclear power has the versatility to provide a range of non-electric services to the whole energy system. These services themselves need to be decarbonized, and the emissions of some could prove hard to abate without a high-temperature, zero-carbon energy source, such as nuclear power. Moreover, experience exists and is growing that some of these services can be provided with nuclear power.

Recommendation 5-1: Industrial applications using thermal energy present an important new mission for advanced reactors. Key research and development needs for industrial applications include assessing system integration, operations, safety, community acceptance, market size as a

function of varying levels of implicit or explicit carbon price, and regulatory risks, with hydrogen production as a top priority. The Department of Energy, with the support of industry support groups such as the Electric Power Research Institute and the nuclear vendors, should conduct a systematic analysis of system integration, operation, and safety risks to provide investors with realistic models of deployment to inform business cases and work with potential host communities.

Finding 5-2**:** Process heat applications exist at a variety of temperature ranges. Higher-temperature applications are likely going to be more difficult to electrify, because there are fewer available low-carbon heat options. Reactor systems with higher outlet temperatures could conceivably serve processes requiring temperatures between 300°C and 800°C. These reactors would need to demonstrate a high degree of safety with minimal reactivity feedbacks between the reactor and the process heat application. These are necessary attributes for siting a nuclear plant near a facility for industrial heat applications.

Finding 5-3**:** Several proposed non-electric services, such as low-temperature heat and desalination, currently cost very little and likely would not be compensated at a level that encourages new nuclear deployment. Hydrogen provides perhaps the most credible non-electric revenue stream for nuclear reactors, because it is likely that hydrogen will have value across the industrial, power, and transportation sectors for deep decarbonization.

CHAPTER 6

Finding 6-1**:** Significant expansion in the deployment of advanced reactor technologies to achieve decarbonization goals will require concomitant growth in the labor force to support not only the construction and operation of these systems, but also to enable the necessary expansion of supporting fuel and supply chains and regulatory and training networks. Development of a wide range of unique technologies may exacerbate this challenge.

Recommendation 6-1: In anticipation of the necessary expansion in workforce to support more widespread deployment of nuclear technologies, the Department of Energy should form a cross-department (whole of government) partnership to address workforce needs (spanning the workforce from technician through PhD) that is comparable to initiatives like the multi-agency National Network for Manufacturing Innovation. The program would include the Departments of Labor, Education, Commerce, and State, and would team with labor organizations, industry, regulatory agencies, and other support organizations to identify gaps in critical skills and then fund training and development solutions that will close these gaps in time to support more rapid deployment. In carrying out these efforts, it will be important to take full advantage of existing efforts at commercial nuclear facilities and national laboratories that already have well-established training and workforce development infrastructure in place.

Finding 6-2**:** The typical U.S. utility company is not adequately equipped with skilled technical and engineering personnel to plan and manage its own major nuclear construction project. Historical evidence suggests that severe cost and schedule overruns are the result of a lack of these in-house capabilities by the primary owner and operator of challenging projects.

Finding 6-3**:** Irrespective of deployment model and reactor technology, installation at a specific site will require planning, compliance with environmental regulations and security requirements, consideration of societal concerns, and adaptation to site-specific conditions such as seismic, geologic, groundwater, elevation of the site with respect to adjacent bodies of water, and severe weather considerations.

Recommendation 6-2: Nuclear owner/operators pursuing new nuclear construction should consider the creation of a consortium or joint venture to pursue the construction on behalf of the group,

thereby enabling the creation and maintenance of the necessary skilled technical engineering personnel to pursue projects successfully. Alternatively, advanced reactor developers operating within the traditional project delivery model should consider implementing a long-term business relationship, preferably an equity partnership such as a joint venture, or a consortium, with a qualified engineering, procurement, and construction firm experienced in the nuclear industry.

Recommendation 6-3: Department of Energy programs such as the Advanced Reactor Demonstration Program should develop criteria that encourage and incentivize all major government-funded nuclear power projects to include a formal collaborative agreement between the reactor vendor and an experienced development firm to ensure that there is management capacity to complete nuclear construction projects successfully, on budget, and on schedule.

Finding 6-4**:** Underestimation of cost, schedules, and risk during the project planning and execution stages can set unrealistic expectations, potentially damaging future prospects for the technology. By ignoring or undervaluing risk, the cost and schedule expectations may not be founded in sound engineering and project delivery expertise.

Recommendation 6-4: The plant owner should mandate an independent peer review involving both a quantitative risk assessment and a qualitative review as part of the plant construction project planning process, especially during a first-of-a-kind new build or first building of an existing design that has had significant changes since it was last built. These could fall under the auspices of the American Society of Mechanical Engineers and the National Reactor Innovation Center, respectively, with assistance from academia and other research organizations (e.g., the Electric Power Research Institute) in the development of the tools and methods. The qualitative independent review should include technical and programmatic risk (to include quality of vendor-fabricated components), the validity of cost estimation elements, schedule realism, and the impact of these on cost; the quantitative risk assessment should include stochastic modeling for schedule and cost estimates. Similar reviews should be conducted when the cost and schedule estimates are more mature, at both 35 percent and 95 percent design completion.

Finding 6-5**:** Although cost and schedule overruns tend to manifest in the construction phase, the causes are often created during the prior planning engineering and procurement phases based on issues such as inadequate design review, component qualification issues, and inadequate installation instructions. This issue is compounded by the fact that there is no readily accessible evidence (e.g., lessons-learned data) that would support and enhance the industry-wide learning that can lead to improved cost and schedule performance over time for nuclear projects in the United States.

Recommendation 6-5: The Department of Energy (DOE) Office of Project Management should partner with an appropriate organization such as the Electric Power Research Institute (EPRI) to build on their lessons-learned repository to provide reactor developers with guidance for risk identification, assessment, and mitigation based on historical occurrences and industry-wide experience. The repository should include a Standard Risk Register for DOE's recent nuclear facilities projects and for nuclear power plant construction (to be developed by the National Reactor Innovation Center), and a standard of practice for nuclear power engineering, procurement, and construction (EPC) projects (perhaps developed by EPRI and Nuclear Energy Institute). The American Nuclear Society should be encouraged to provide development of a nuclear EPC learning and engagement track.

Finding 6-6**:** Incomplete design or late design changes can lead to significant schedule and cost growth.

Recommendation 6-6: Advanced nuclear developers should follow a criteria-based approach to ensure that detailed designs are >95 percent complete before transitioning to full project execution. This approach can be made actionable by the owner through insistence on a more comprehensive assessment of design readiness, including manufacturability of components and adequacy of build materials like concrete and rebar.

Finding 6-7**:** The supply chain supporting the current fleet of operational nuclear power plants in the United States does not currently have the capacity to provide the unique components necessary for different reactor designs while maintaining sufficient quality, considering the number of builds envisioned by reactor developers. The lack of sufficient manufacturing capacity with strict quality assurance programs poses challenges for both product- and project-based deployment models. Expansion of the supply chain would necessitate implementation of Nuclear Quality Assurance (NQA-1) requirements across an enlarged manufacturing base.

Finding 6-8**:** Digital engineering tools (including but not limited to digital twins) and building information modeling are focused on removing uncertainties that add to cost and schedule during the planning phase by facilitating coordination among all stakeholders and bringing transparency to construction performance. Such innovations could assist with timely identification of quality issues such as tolerances, thus permitting near real-time decisions on acceptance or rejection of the components during installation, which may reduce cost and schedule impacts. Further research on digital engineering tools is needed to determine the value of implementing them in advanced reactor installations.

Recommendation 6-7: The Department of Energy's Office of Nuclear Energy and Advanced Research Projects Agency–Energy as appropriate should enhance collaboration among entities currently researching and developing digital engineering technologies to support improved vendor fabrication and certification of components. This effort should identify specific capacities that would help nuclear builds in particular.

Finding 6-9**:** There are significant R&D efforts under way in advanced manufacturing technology development and advanced processes funded through the Department of Energy (DOE) Building Technologies Office and the Advanced Manufacturing Office. Better alignment of these efforts with the DOE Office of Nuclear Energy's programs may support lower-priced and more streamlined construction of new nuclear sites.

Finding 6-10**:** Numerous analyses have found that site development challenges have been a primary contributor to cost and schedule overruns for nuclear deployment. Despite this recognition, there is limited R&D activity to develop technologies that can reduce cost and risk in site development that is focused on nuclear plants. For example, $5.8 million was allocated in FY 2022 for the Advanced Construction Technologies Initiative, and some limited funding was provided for materials/manufacturing research (non-specific to site construction) within the Advanced Materials and Manufacturing Technologies Sub-Program portion of the Cross Cutting technologies program. This is dwarfed by the broader non-nuclear-specific programs under way examining advanced production processes and building design processes funded through the Department of Energy Building Technologies Office and the Advanced Manufacturing Office.

Recommendation 6-8: While it is vital to demonstrate that advanced reactors are viable from a technical perspective, it is perhaps even more vital to ensure that the overall plant, including the onsite civil work, can be built within cost and schedule constraints. Because it is likely that costs for onsite development will still be a significant contributor to capital cost, and the ~$35 million in Department of Energy (DOE) funding for advanced construction technologies R&D is small in comparison to the hundreds of millions spent on nuclear island technology research, more should

be done over an extended period to research technologies that may streamline and reduce costs for this work. DOE should expand its current efforts in R&D for nuclear construction and make these advanced technologies broadly available, including to vendors participating in the Advanced Reactor Demonstration Program Risk Reduction and ARC20 programs.

Finding 6-11**:** A highly standardized product-based approach could improve learning, cost and schedule performance, quality, and speed and scale of reactor deployment. However, the data used to make cost and risk estimates are often based on the assumption that plants are sited at locations with similar characteristics, which will not always be the case.

Finding 6-12**:** There is currently limited U.S. domestic capability to support a product-based approach to building nuclear reactors outside the naval shipyard environment, although some existing nuclear facilities could be modified to support a manufacturing model and international teaming may be possible.

Recommendation 6-9: The Department of Energy should work with the relevant reactor vendors to develop best practices for the pursuit of a product-based approach to reactor deployment.

Finding 6-13**:** Advanced reactor developers are considering a manufacturing "shipyard" approach to modular development to better control costs in development. While historical assessments do indicate that a production line approach as seen in shipyard production can lead to cost savings, it is unclear whether this approach will translate to significant cost savings in advanced reactor development because it does not necessarily address site development, which can be a primary cost driver in nuclear deployment.

Recommendation 6-10: The Department of Energy should partner with the Department of the Navy and industry to evaluate lessons learned in nuclear shipbuilding to determine the metrics and cost factors that would inform a better understanding of potential cost savings from a manufacturing approach to nuclear new builds. The evaluation would focus specifically on how the engineering facility is set up to enable efficient multiple unit throughput, with considerations to both workforce optimization and setup of internal lines within the facility. Outcomes could include development of standardized tools and analytic methods that would enable better assessment of readiness for commercialization across different nuclear technologies and inform the business cases for development of a nuclear manufacturing facility.

CHAPTER 7

Finding 7-1**:** In recognition that advanced reactors present different regulatory issues from light water reactors, the U.S. Nuclear Regulatory Commission (NRC) is allowing a degree of regulatory flexibility under the existing regulatory system (NRC Part 50 and Part 52). It is also pursuing a technology-independent, performance-based, and risk-informed regulatory process for advanced reactors to be promulgated as Part 53. These actions reflect reasonable flexibility by the NRC to adjust the regulatory system to accommodate reactors different from existing light water reactors.

Finding 7-2**:** Establishing the safety case for an advanced reactor will require a thorough verification of the validity of safety claims based on detailed analyses founded on experimental data. All should recognize that the U.S. Nuclear Regulatory Commission will take its obligation to ensure adequate protection of public health, safety, and environment seriously and that the necessary thorough review of applications can be time consuming.

Recommendation 7-1: Advanced reactors will not be commercialized if the regulatory requirements are not adjusted to accommodate their many differences from existing light water reactors. A clear

definition of the regulatory requirements for a new technology must be established promptly if timely deployment is to be achieved. The U.S. Nuclear Regulatory Commission (NRC) needs to enhance its capability to resolve the many issues with which it is and will be confronted. In recognition of the urgency for the NRC to prepare now, Congress should provide increased resources on the order of tens of millions of dollars per year to the NRC that are not drawn from fees paid by existing licensees and applicants.

Recommendation 7-2: The U.S. Nuclear Regulatory Commission should undertake a lessons-learned effort as it processes the first group of applications for advanced reactors as a means to streamline its review without compromising its commitment to the public health, safety, and the environment.

Finding 7-3**:** There is a need to ensure a balance between staged licensing and efficiency in the licensing process. The existing process of providing intermediate, but non-final, resolution of matters by the U.S. Nuclear Regulatory Commission staff is a reasonable and practical compromise to provide timely and informed input to license applicants.

Finding 7-4**:** International sales may be an essential part of the business plans of some vendors. Regulatory requirements that differ from country to country can inhibit international sales.

Recommendation 7-3: In light of the importance of international markets, significant efforts should be undertaken now to reconcile needless differences in licensing obligations from one country to another. This should involve increased engagement with the International Atomic Energy Agency and the Nuclear Energy Agency on these matters, as well as exploration of regulatory mechanisms like those used by the aviation industry. In the meantime, bilateral arrangements with other countries pursuing advanced reactors, such as the memorandum of understanding that the United States has entered with Canada, may pave the way for broader international harmonization.

Finding 7-5**:** Some reactor vendors anticipate opportunities to deploy their reactors near or in urban environments or in the vicinity of industrial facilities that will use heat produced by the reactor. These applications of advanced reactors will present unique siting and emergency planning issues. Careful and early examination of such issues is necessary to define the future range of economic opportunities that are available for advanced reactors.

Recommendation 7-4: The U.S. Nuclear Regulatory Commission should expedite the requirements and guidance governing siting and emergency planning zones to enable vendors to determine the restrictions that will govern the deployment of their reactors.

Finding 7-6**:** Some advanced reactors are likely to present unique and difficult decommissioning challenges.

Recommendation 7-5: Reactor developers need to consider the challenges associated with decommissioning and address them in the reactor design. The failure to consider decommissioning issues in the design phase could result in large expenses at the end of a reactor's life. Vendors should exploit the lessons learned from Department of Energy and Department of Defense decommissioning activities, as well as from the decommissioning of power and research reactors.

Finding 7-7**:** Some vendors propose to use novel fuels for which limited experimental or operational data is available. This is likely to present a particular regulatory challenge because of the need for extended fuel irradiation to provide the data necessary to support the safety case for the designs. Moreover, the development of the necessary fuel cycle infrastructure will require extensive new regulatory activity.

CHAPTER 8

Finding 8-1**:** A successful deployment of advanced nuclear energy will require technologies that meet a specific market need at an economic price and that integrate safety, safeguards, and security into the design. Far less appreciated, but likely as critical, is the need to integrate public participation and consent into design, siting, and long-term operations.

Recommendation 8-1: Socio-technical approaches should become part of the nuclear energy research and development (R&D) cycle, treated with the same seriousness as technological development. Research programs need to be reimagined to include public engagement starting at early innovation and through planning, design, deployment, and operation. These programs should be endogenous to the R&D cycle (rather than added on) and should be taken seriously and done rigorously. The Department of Energy should update its programs and associated budget requests to include social science along with their traditional physical science and engineering research. This should lead to the establishment and support of a national cohort of scholars leading in the socio-technical aspects of nuclear energy use.

Finding 8-2**:** There exists significant tension between the secrecy and security required by the institutions that develop, deploy, and regulate nuclear power—and the transparency and openness that are hallmarks of best siting practices and community support. This is inevitable, but resolving or managing the tension would support efforts to expand nuclear power, especially if plans for widespread national or international deployment are envisioned.

Finding 8-3**:** Risk communication strategies that rely exclusively or greatly on the engineer's myth and the deficit model of science communication have been tried in the nuclear industry and have failed comprehensively.

Recommendation 8-2: To improve the prospects for nuclear deployment in coming decades, nuclear vendors need to employ new risk communication strategies, including those grounded in rigorous social science (rather than polling) and respect for community apprehensions and desires. Moreover, risk communication strategies need to remain robust and endure for the life of a nuclear plant, not just during construction. Different methods and frameworks for engagement may be required in each phase of a plant's lifetime.

Finding 8-4**:** Academic training in nuclear engineering, and in many engineering fields broadly, has focused on deep technical training without sufficient considerations of the social consequences of engineering decisions.

Recommendation 8-3: U.S. academic institutions need to take the lead in promoting socially conscious engineering. Within the nuclear energy field, the Nuclear Engineering Department Heads Organization and the American Nuclear Society Education, Training, and Workforce Development Division should engage with experts in the social sciences of design and siting to collaborate, develop, and implement a set of recommendations for updating curriculum, accreditation, scholarship and fellowship programs, as well as research programs. This includes economics, ethics, social science, and the importance of historical decisions and practices that left negative impressions of nuclear technology. While integrated engineering teams should include a broad range of experts crossing many disciplines, engineers, who often lead design teams, should be trained to appreciate the social components of design choices.

Finding 8-5**:** Empirical evidence (in the form of new conceptual reactor designs proposed over the past two decades) suggests that public engagement during design and designing for values remains far removed from how nuclear reactor designers approach their tasks; this is especially true for engineers who are trained to focus on technical issues.

Recommendation 8-4: The advanced nuclear industry, guided by experts who understand the effect of social interactions on design choices, should devote resources to public engagement during the front-end design phase to ensure that products are best aligned with values. This might minimize the opposition to the licensing process for any specific site. To maximize the probability that a specific design is acceptable to the largest number of communities, reactor designers must engage with potential host sites well in advance of submitting their design certification documents to the regulator: only then could they realistically address public concerns and mitigate them in their proposed plans. This does not mean that each site needs a different design, but that community concerns broadly are considered while designing a nuclear energy system.

Finding 8-6**:** The advanced reactor community in the United States is still in its nascency, and therefore has no experience in dealing with potentially challenging siting issues associated with (1) constructing a variety of new nuclear reactor designs at many new locations inexperienced with nuclear power and (2) deploying a variety of novel operational paradigms that are different from nuclear power's traditional role as a baseload electric power generator.

Recommendation 8-5: The developers and future owners that represent the advanced nuclear industry should adopt a consent-based approach to siting new facilities. The siting approach will have to be adjusted for a particular place, time, and culture. The nuclear industry should follow the best practices, including (1) a participatory process of site selection; (2) the right for communities to veto or opt out (within agreed-upon limits); (3) some form of compensation granted for affected communities; (4) partial funding for affected communities to conduct independent technical analyses; (5) efforts to develop a partnership to pursue the project between the implementer and local community; and (6) an overriding commitment to honesty. Following these practices will require additional time and financial resources to be allotted to successfully site and construct new nuclear power facilities, and the industry should account for these costs in their plans. The industry should be willing to fully engage with a community, hear its concerns and needs, and be ready to address them, including adjusting plans. While this would raise the likelihood of successful deployment, it is not a guarantee of success. Additionally, the industry, guided by experts in consent-based processes, should capture best siting practices in guidance documents or standards.

CHAPTER 9

Finding 9-1**:** The U.S. Nuclear Regulatory Commission (NRC) staff has proposed significant modifications to physical security requirements to accommodate designs and operations proposed by licensees of advanced reactors that differ from larger light water power reactors. There are many hurdles, including new assessments without clear NRC guidance on compliance demonstrations and a fuller understanding of the vulnerabilities that the new designs and deployment scenarios may present. These issues must be evaluated and any capacity/capability shortfalls in NRC expertise must be overcome before any such modifications can be applied by vendors.

Recommendation 9-1: The modification of the security requirements proposed by the U.S. Nuclear Regulatory Commission (NRC) staff could have significant implications for the design, staffing, and operations of advanced reactors, thereby impacting business plans. Delays in providing clear regulatory guidance may impact capital availability and increases the potential for costly redesign

if guidelines do not align with expected modifications to existing protocols. Congress should provide additional funding for NRC evaluation of security guidelines and NRC should expedite its consideration of the staff proposal and seek to complete the rule making promptly if significant changes are deemed appropriate. In that case, the prompt completion of the associated guidance should also be a high priority.

Finding 9-2**:** Advanced reactor designers envision increased use of automation and the potential for use of artificial intelligence–enabled sensors and controls to reduce staff costs, enhance the robustness of defenses, and, in some cases, provide for remote, multi-asset operations. These systems could increase cybersecurity risk, with some resulting security cost burden over the operating life of the reactor.

Recommendation 9-2: The U.S. Nuclear Regulatory Commission (NRC) must ensure the safety and security of new designs, especially for designs that employ greater automation and incorporate remote operating options. Claimed cybersecurity protocols should be tested and regularly validated across the full life cycle of the facility. Licensees should incorporate sufficient cybersecurity controls to ensure safety and guarantee asset protection and manufacturing facility protection across the product life cycle. Both the NRC and the vendors should work closely with the International Atomic Energy Agency's Small Modular Reactor and Instrumentation and Control Systems groups to develop international standards and determine whether new monitoring alternatives are needed.

Finding 9-3**:** As advanced reactors continue to be developed with the potential of rapid scale-up both domestically and internationally in the coming decades, it is crucial to recognize, prioritize, and address potential gaps in safeguards technology and to incorporate key measurement capabilities at the earliest stages of the design process. Several initiatives in the United States and within the International Atomic Energy Agency have begun to address these challenges.

Recommendation 9-3: The International Atomic Energy Agency (IAEA) and Department of Energy (DOE) should identify the funding, personnel, regulatory analyses, and key technology gaps for pilot programs in international safeguards for advanced reactors. There is also a need for the vendors to engage early in their designs to fully understand IAEA safeguards requirements and implementation. Because the first vendors will bear the largest cost burden in developing and implementing safeguards for new advanced reactor designs that other vendors may incorporate, the IAEA and DOE should develop cost incentive-based programs to encourage early-adopter vendor participation in safeguards development.

Finding 9-4**:** Consideration of safety, security, and safeguards requirements—individually as well as their interactions—at the beginning of and throughout the advanced reactor design process by the vendors will avoid unnecessary costs and complications.

Recommendation 9-4: Vendors bear the responsibility of demonstrating compliance of their designs with safeguards, security, and safety requirements, including International Atomic Energy Agency safeguards requirements for reactors sold to non-weapons states. Vendors should recognize that these requirements are interrelated with each other and should ensure that any necessary trade-offs are made early in the design process.

Finding 9-5**:** The U.S. government has established a robust set of programs and organizations that will support advanced reactor developers across the spectrum of research, development, and deployment, including support for domestic and international safeguards and security research, international engagement, and licensing assessment. In addition, the United States and the International Atomic Energy

Agency have initiated complementary programs to support the long-term effort needed to develop effective nuclear frameworks for the deployment of new and advanced reactors.

Recommendation 9-5: The United States should develop a plan for increased and sustained long-term financial and technical support for capacity building in partner countries, including cost requirements for using U.S. national laboratories and universities as training platforms. This plan should include partnering with U.S. reactor vendors to develop a safety, safeguards, and security "package," where the United States and the vendor could offer customized support to a host country for developing and implementing new safety, safeguards, and security arrangements.

CHAPTER 10

Finding 10-1**:** 123 Agreements provide a foundation for the eventual transfer of nuclear items from the United States to existing and emerging nuclear-capable countries. Negotiations typically take years and require the application of significant diplomatic resources. Once a 123 Agreement has entered into force, three main U.S. export control processes are used to authorize or license nuclear exports: Part 810 (Department of Energy), Part 110 (Nuclear Regulatory Commission), and Export Administration Regulations (Department of Commerce). Each licensing or authorization process adds additional time, from as little as 90 days to more than 9 months. Therefore, obtaining U.S. export licenses—from negotiation of a 123 Agreement through exchanges of design information (Part 810) to reactor construction—may take at least several years for the first nuclear export to a country, particularly for a first-of-a-kind reactor plant design.

Finding 10-2**:** The U.S. federal agencies—Department of Energy, Nuclear Regulatory Commission, and Department of Commerce—working on the different licensing and authorization processes regularly speak and work with one another when presented with an application. This close coordination across these lead agencies has several benefits: it may reduce the need for extensive modification to manage the export of new and advanced reactors and their technologies, and, given that the export of any individual advanced reactor by a U.S. vendor would likely involve all three licensing processes, this interaction across the agencies plays an important role in ensuring that decisions in one process do not work at cross-purposes with the two other licensing processes. There is little evidence, however, that these agencies have offered coordinated and targeted outreach efforts to U.S. vendors of new and advanced reactors.

Recommendation 10-1: Efforts should be made to shorten the timelines for putting in place 123 Agreements and review of export applications. The three lead export control agencies should increase efforts to educate U.S. nuclear vendors on the requirements, bureaucratic resources, and timelines associated with U.S. 123 Agreements and U.S. nuclear export controls. These efforts would include the creation of new specialized guidance materials, training activities, and other forms of technical assistance, especially for new vendors and in coordination with Gateway for Accelerated Innovation in Nuclear and similar initiatives, in anticipation of new license applications.

Finding 10-3**:** As some growth scenarios indicate, there could be a significant increase in the number of deployed advanced reactors throughout the world by 2050. Because no single country (or no single vendor within a country) is likely to be able to support the entire international marketplace, all competitors and competitor nations should recognize that they have shared responsibility in minimizing safety, security, and safeguards risks.

Finding 10-4**:** For U.S. vendors to better compete with state-owned or state-financed vendors in the dynamic international energy market, a technically and economically viable product must be established that could then be supported by a robust and reliable source of export credit financing. Non-U.S. vendors have more options for financing the export and deployment of advanced reactors than U.S. vendors. This imbalance will eventually reduce the competitiveness of the United States' advanced reactors in the international marketplace, which could limit the opportunities to build successful partnerships that the United States has used effectively to promote U.S. national security and global nuclear safety, security, and safeguards. Exploring non-standard financial mechanisms and ownership models, such as Build Own Operate (BOO) or Build Own Operate Transfer (BOOT), could be useful in non-Organisation for Economic Co-operation and Development (OECD) markets.

Finding 10-5**:** Most U.S. advanced reactor vendors will not be ready for international commercial deployment until after successful demonstrations in the United States and thus will be unlikely to tap export-import bank financing before a new authorization cycle is necessary. Given the political challenges that occurred from 2015 to 2019, vendors may not view this as a reliable source absent action by Congress to stabilize and expand funding further.

Recommendation 10-2: International nuclear projects by U.S. exporters are likely to require a financing package that reflects a blending of federal grants, loans, and loan guarantees along with various forms of private equity and debt financing. The Executive Branch should work with the private sector to build an effective and competitive financing package for U.S. exporters.

Finding 10-6**:** Increasing harmonization in developing and interpreting international nuclear export control guidelines as they apply to advanced reactors by nuclear suppliers will help equalize regulatory requirements facing U.S. and non-U.S. vendors.

Recommendation 10-3: The three lead U.S. export control agencies (Department of Energy, Nuclear Regulatory Commission, Department of Commerce) should continue to support initiatives within the International Atomic Energy Agency and Nuclear Suppliers Group (e.g., technical exchanges, guidance reviews, and regular meetings) to monitor and promote harmonized implementation and interpretation of export control, safety, security, and safeguards guidelines. Increased commitment of U.S. resources to the three lead export control agencies will be needed to support the work of the Nuclear Suppliers Group on new and advanced reactors, including resources for and leadership in a review of new materials and technologies in conjunction with an internal U.S. review of these items.

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Public Meetings

PUBLIC MEETING 1, VIRTUAL
DECEMBER 17, 2020

Topic: Laying the Foundation for New and Advanced Nuclear Reactors in the United States Statement of Task
Speakers:

- Alice Caponiti, Department of Energy—Office of Nuclear Energy
- Tim Beville, Department of Energy—Office of Nuclear Energy
- John Wagner, Idaho National Laboratory
- Alyse Huffman, House Science, Space, and Technology—Energy Subcommittee
- Scott McKee, House Appropriations—Energy and Water Subcommittee
- Rory Stanley, Senate Energy and Natural Resources Committee
- Ho Nieh, U.S. Nuclear Regulatory Commission—Office of Nuclear Reactor Regulation

PUBLIC MEETING 2, VIRTUAL
JANUARY 25, 2021

Topic: Financing Challenges for New and Advanced Nuclear Reactors
Speakers:

- John Parsons, Massachusetts Institute of Technology—Low Carbon Energy Center on Advanced Nuclear Energy Systems
- Matt Bowen, Columbia Center on Global Energy Policy
- Ray Rothrock, RedSeal, Inc.

PUBLIC MEETING 3, VIRTUAL
APRIL 5–6, 2021

Topic: Nuclear Power Plant Construction Challenges and Lessons Learned
Speakers:

- Hee Yong Lee, Korea Electric Power Corporation
- Simon Marshall, Independent Nuclear Expertise, Ltd.
- Frederick Brown, U.S. Nuclear Regulatory Commission (retired)
- Abhinav Gupta, North Carolina State University—Center for Nuclear Energy Facilities and Structures

- Kevin Han, North Carolina State University—Center for Nuclear Energy Facilities and Structures
- Chris Ritter, Idaho National Laboratory— Digital Innovation Center
- Ed Merrow, Independent Project Analysis, Inc.
- Joseph Brewer, Dow Chemical (retired)

PUBLIC MEETING 4, VIRTUAL
MAY 26–27, 2021

Topic: ARDP Demo Winners Terra Power and X-Energy, and a Discussion with the Department of Defense on Project Roles
Speakers:

- Eben Mulder, X-Energy
- Ben Reinke, X-Energy
- Chris Levesque, TerraPower
- Tara Neider, TerrPower
- Eric Wesley, Flyer Defense, LLC
- Jeff Waksman, Department of Defense—Strategic Capabilities Office

PUBLIC MEETING 5, VIRTUAL
JUNE 16, 2021

Topic: Future of Electric Power Briefing
Speakers:

- Granger Morgan, Carnegie Mellon University
- Anjan Bose, Washington State University

PUBLIC MEETING 6, VIRTUAL
JULY 14, 2021

Topic: Open Session with NuScale Power
Speaker:

- José Reyes, NuScale Power

PUBLIC MEETING 7, VIRTUAL
JULY 19-20, 2021

Topic: Grid Integration and Alternative Value Streams
Speakers:

- John Bistline, Electric Power Research Institute
- Marilyn Kray, Exelon Generation
- Lauren Lathem, Southern Company
- Eric Ingersoll, LucidCatalyst
- Chad Bouer, Electric Power Research Institute
- Lisa Lamber, Eastman Chemical

- David Bustetter, Eastman Chemical
- Gordon van Welie, ISO-New England
- Tyler Westover, Idaho National Laboratory
- Dan Ludwig, Xcel Energy
- Andrew Sowder, Electric Power Research Institute

PUBLIC MEETING 8, VIRTUAL
SEPTEMBER 1–3, 2021

Topic: Understanding the Societal Challenges Facing Nuclear Power Workshop
Speakers:

- Thomas R. Wellock, U.S. Nuclear Regulatory Commission
- Spencer R. Weart, American Institute of Physics (retired)
- M.V. Ramana, University of British Columbia
- Baruch Fischhoff, Carnegie Mellon University
- Nick Pidgeon, Cardiff University
- Seth Tuler, Worcester Polytechnic Institute
- Sheila Jasanoff, Harvard University
- Behnam Taebi, TU Delft
- Andy Stirling, University of Sussex
- Pierre-Benoit Joly, French Institute for Research and Innovation in Society
- Sarah Mills, University of Michigan
- John Downer, University of Bristol
- David Victor, University of California—San Diego
- Saida Laârouchi Engrström, Swedish Nuclear Fuel and Waste Management Company
- Arne Kaijser, KTH Royal Institute of Technology
- Anne Bergmans, University of Antwerp
- Doug Hunter, UAMPS
- Mary Woollen, Ultra Safe Nuclear Corporation
- Christi Bell, University of Alaska—Business Enterprise Institute

PUBLIC MEETING 9, VIRTUAL
OCTOBER 4–5, 2021

Topic: Security, Safeguards, and International Issues for New and Advanced Reactors
Speakers:

- Jessica Jewell, University of Bergen
- James Warden, State Department
- Kirsten Laurin-Kovitz, Argonne National Laboratory
- Ben Cipiti, Sandia National Laboratories
- Anagha Iyengar, National Nuclear Security Administration
- Jessica Bufford, Nuclear Threat Initiative
- Alvaro Acevedo, World Institute for Nuclear Security
- Michele Sampson, U.S. Nuclear Regulatory Commission
- Victor Gilinsky, Nonproliferation Policy Education Center
- Elina Teplinsky, Pillsbury Law

- Kevin Veal, National Nuclear Security Administration
- Peter Habighorst, U.S. Nuclear Regulatory Commission
- Katie Strangis, National Nuclear Security Administration
- Steven Clagett, Commerce Department
- James Warden, State Department
- Mirjam Kochendröfer, Nuclear Suppliers Group
- Brent Heilman, Argonne National Laboratory and Nuclear Suppliers Group
- Carol Berrigan, Nuclear Energy Institute
- David Victor, University of California San Diego

PUBLIC MEETING 10, VIRTUAL
NOVEMBER 15, 2021

Topic: National Reactor Innovation Center Open Session
Speaker:

- Ashley Finan, National Reactor Innovation Center

PUBLIC MEETING 11, VIRTUAL
FEBRUARY 1–2, 2022

Topic: Conversations with Advanced Reactor Vendors
Speakers:

- Jonathan Cirtain, BWXT
- David LeBlanc, Terrestrial Energy USA
- Edward Blandford, Kairos Power
- Per Peterson, Kairos Power
- Rick Springman, Holtec International
- Jacob DeWitte, Oklo
- Rory O'Sullivan, Moltex Energy
- Janne Wallenius, LeadCold
- Farshid Shahrokhi, Framatome

PUBLIC MEETING 12, VIRTUAL
FEBRUARY 15, 2022

Topic: Army Energy and Sustainability Open Session
Speaker:

- Jack Surash, U.S. Army