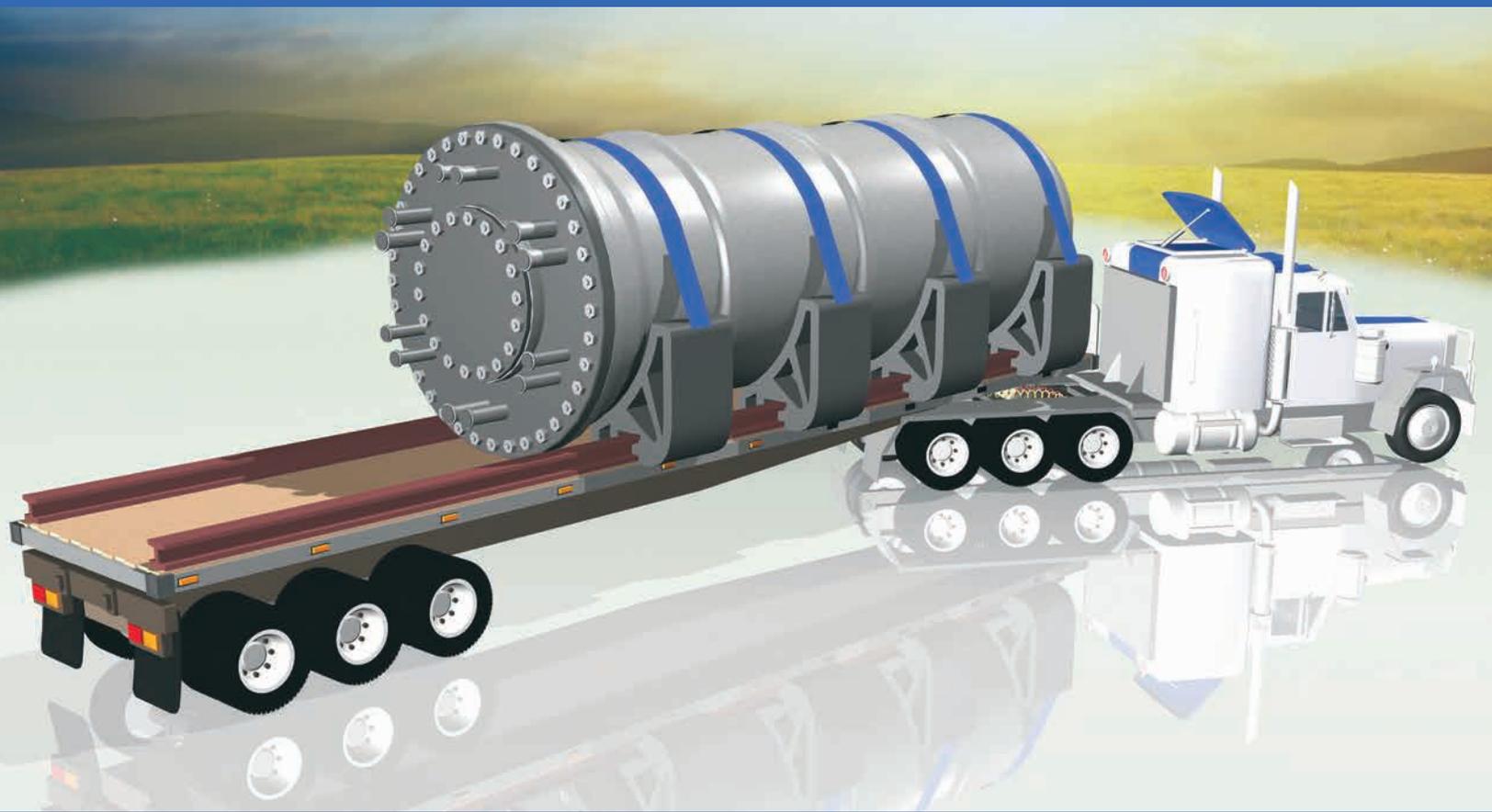


Enabling Nuclear Innovation **Leading on SMRs**



**A Report on Small Modular Reactors
by the Nuclear Innovation Alliance**

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AUTHOR

Matt Bowen, Ph.D., Nuclear Innovation Alliance



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October 2017

Enabling Nuclear Innovation:
Leading on SMRs

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COVER IMAGE

Adapted from an illustration, provided courtesy of Oak Ridge National Laboratory, of a truck transporting a Small Modular Advanced High Temperature Reactor (SmaHTR) module.

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DISCLAIMER

Reviewers were not asked to concur with the judgments or opinions in this report. All remaining errors are the author's responsibility alone.

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EXECUTIVE SUMMARY

A CENTRAL CHALLENGE IN THE 21st Century is how to lift billions of people out of poverty without long-term damage to human health and the environment. Increased energy use has been linked to improvements in quality of life, and one consequence of that connection is clear: worldwide demand for energy, especially in the developing world, is predicted to increase substantially out to 2050. Fossil fuels currently supply roughly 85% of the energy

Small modular reactors offer lower overall costs, shorter construction periods, and simplified designs that enhance safety.

that drives the world economy. With the traditional use of that energy source, however, comes serious air pollution and climate change risks. Nuclear energy is a dispatchable source of clean energy with decades of operational experience that could help to reduce these environmental risks, while supplying the energy necessary to spur economic growth that can advance quality of life worldwide. And one particular technology—small modular reactors (SMRs)—offers great promise.

In the past, the complexity of large light-water reactor designs contributed to construction delays, as it has with the most recent U.S. construction projects. SMRs offer lower overall costs, shorter construction periods, and simplified designs that

enhance safety. They offer the potential to set new standards for passive nuclear energy safety in the U.S. commercial fleet, while their operational flexibility supports reliability of the electrical grid in an era of rising intermittent renewable energy generation. Through industrial heat applications, SMRs could potentially decarbonize sectors beyond electricity and contribute to nuclear/renewable hybrid energy systems.

In this report, SMRs are defined by their size, co-location of multiple modules, and approach to construction, rather than by coolant. In other contexts, SMRs may specifically mean light-water cooled designs, but here they include light-water cooled along with liquid metal, gas, and molten salt reactors. (See Chapter II: The Small Modular Reactor Option for further discussion.)

Natural gas combined cycle (NGCC) plants are the least expensive of any generation source in the current U.S. market, given the low price of natural gas. The levelized cost of electricity (LCOE) for a given energy technology is one measure of that technology's competitiveness against other energy sources.¹ The LCOE comparison for SMRs versus NGCC plants depends to a significant degree on the regulatory environment for electricity generation, as well as the specific financing structure for construction. While the LCOE for SMRs is much higher than NGCC plants in deregulated states, it narrows in other environments. Accounting for the cost of greenhouse gas emissions, SMRs can compete with NGCC plants in the public power sector. Adding SMRs to generating portfolios would also reduce utilities' exposure to natural gas price volatility.

¹ As discussed in Chapter III, LCOE is an imperfect measure of an energy source's value, neglecting factors such as reliability, intermittency, and other issues.

Global public and private sector commitments to deploying cleaner energy technologies underlie various projections showing an increase of hundreds of gigawatts in nuclear energy capacity over the next 23 to 33 years. If SMRs capture even a small portion of total nuclear energy capacity worldwide, and move into process heat applications, the result will be tens of gigawatts or more of SMR deployment. Most of these builds will occur outside the United States, in the developing world, with likely three major SMR suppliers: China, Russia, and the United States. International opportunities could create or sustain hundreds of thousands of U.S. jobs.

The projected growth in nuclear energy generating capacity over the next several decades, including in countries that either do not have existing nuclear energy programs or have only very preliminary ones, has implications for the global nonproliferation regime. Since President Eisenhower's Atoms for Peace speech in 1953, the United States has seen a national interest in providing support for peaceful nuclear energy activities in exchange for a role in setting nonproliferation conditions. Government investment in the 1950s and 1960s paved the way for early U.S. global dominance of the nuclear energy markets, which in turn gave the United States an outsized role in setting nonproliferation supplier norms. With the coming expansion of nuclear power in the developing world, a renewed commitment to leadership in nuclear energy is needed to ensure a similar role for the United States once again.

Given the uncertainty in cost and availability for different nuclear reactor designs, the United States should provide a continuum of support through the different stages of reactor development and use the market to help guide technology down-selection. The federal government should also provide targeted incentives and support to leverage the specific regions and entities in the United States where nuclear energy is most attractive to achieve deployment of first-of-a-kind SMRs. Domestic deployment and U.S. Nuclear Regulatory Commission licensing will provide a marketing advantage to U.S. SMR companies seeking to gain a foothold in international markets. This will ensure that the United States has an active role in the development and evolution of the global nuclear energy and nonproliferation regime over the coming decades, which in turn will support U.S. national security interests.

To further these objectives, the following actions are recommended. (See Chapter VI: Recommendations for further details.) Additional

research, development, and demonstration recommendations needed to support non-light water reactors will be described in greater detail separately.

Recommendation 1: Congress and the Administration should expand support for new reactor design and licensing to include non-light water designs and extend support through design finalization.

Recommendation 2: Congress should amend the nuclear energy production tax credit (PTC).

Congress should amend section 1306 of the Energy Policy Act of 2005 (EPACT05) to remove the in-service date of January 1, 2021, raise the cap to 9000 MW, allow nonprofit public power entities to qualify, and raise the payment rate for new deployments to 2.7 cents/kWh.

Recommendation 3a: Congress should enable federal facilities to enter into power purchase agreements for low-emission technologies for periods of 20 years or greater.

Recommendation 3b: The Secretary of Energy should work with the Western Area Power Administration (WAPA) Administrator and the U.S. Department of Energy (DOE), the U.S. Department of Defense (DOD), and other federal facilities in the WAPA territory to procure 100–200 MW of power from the Utah Associated Municipal Power Systems (UAMPS) SMR project.

Recommendation 3c: The Secretary of Energy should work with the Tennessee Valley Authority (TVA) and DOE, DOD, and other federal facilities in the TVA territory to procure 100–200 MW of power from the TVA SMR project.

Recommendation 3d: DOE should identify options for federal power purchase agreements to help enable deployment of new reactor technologies.

Recommendation 4: States should expand any existing or proposed Renewable Portfolio Standards into Clean Energy Standards. *States should expand renewable portfolio standards into clean energy standards to increase the total amount of low-carbon electricity required and give utilities greater flexibility in reducing air pollution and greenhouse gas emissions, while also meeting reliability requirements.*

CHAPTER 1

WORLD ENERGY CHALLENGES

A CENTRAL CHALLENGE IN THE 21st Century is how to lift billions of people out of poverty without long-term damage to human health and the environment. Increased energy use has been linked to improvements in quality of life, and one consequence of that connection is clear: worldwide demand for energy is predicted to increase substantially over the next few decades. Fossil fuels currently supply roughly 85% of the energy that drives the world economy (Figure 1). The challenges associated with the traditional use of fossil fuels, however, inspire various projections for a potentially greater role for

nuclear energy, and other low-emission technologies, in the coming decades.

A. Projected Growth in Global Energy Consumption

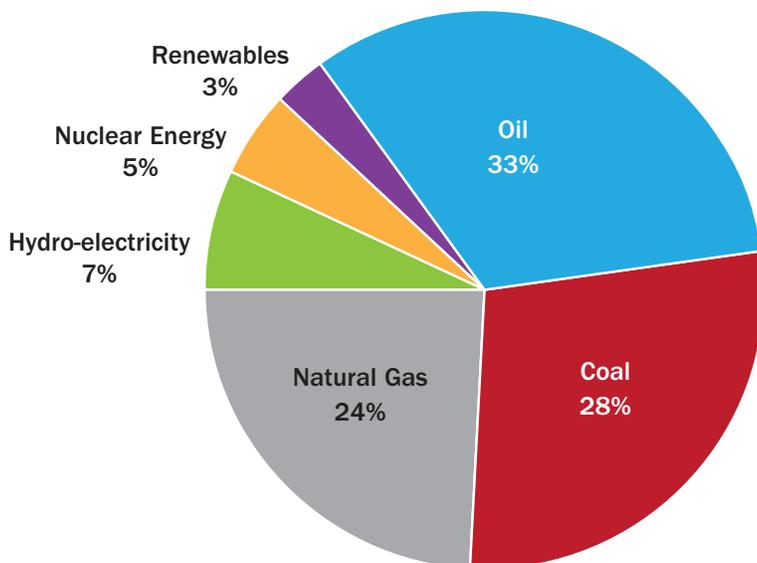
In its 2016 International Energy Outlook, the U.S. Energy Information Administration (EIA) projects that between 2012 and 2040, global energy consumption will rise by 48%. This is mostly driven by non-Organisation for Economic Co-operation and Development (OECD)² nations, where economic and population growth will drive up energy consumption by 71%. Almost two-thirds of worldwide primary energy consumption by 2040 will take place in non-OECD countries.

The International Energy Agency (IEA) estimates that 1.2 billion people are currently without access to electricity and more than 2.7 billion people are without clean cooking facilities. More than 95% of these people are located in either sub-Saharan African or developing Asia, and around 80% are in rural areas.³ These realities, along with others, drive the anticipated increase in energy consumption among developing countries. Higher energy consumption has been linked to increases in quality of life, as shown in Figure 2.

B. Risks with Traditional Energy Use

Historically, economic development has been driven by increased energy use, but the IEA estimates that 6.5 million deaths are attributed each year to associated poor air quality. This makes polluted air the world's fourth-largest threat to human health, behind high blood pressure, dietary risks, and smoking. Energy production and use, mostly

FIGURE 1
2016 World Primary Energy Consumption by Fuel

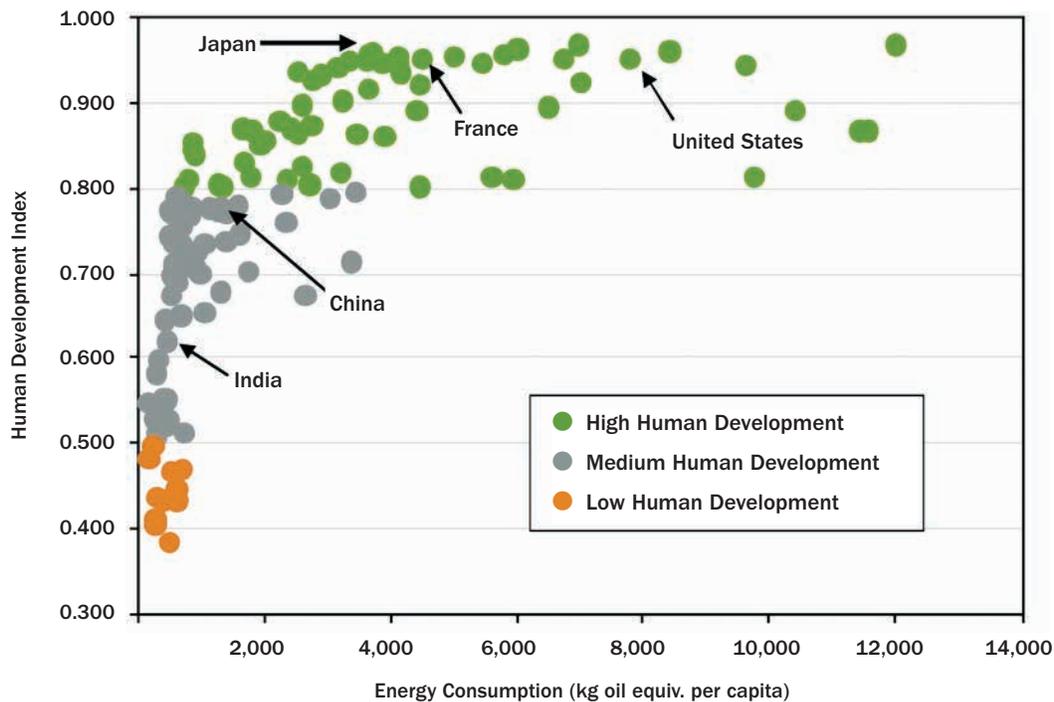


Source: Page 9 of BP Statistical Review of World Energy, June 2017.

² There are 35 members of the OECD and each country tends to have a relatively high income and a high human development index.

³ <https://www.iea.org/topics/energypoverty>; accessed on August 17, 2017.

FIGURE 2
Human Development Index Versus Energy Consumption



Source: DOE, "Office of Nuclear Energy R&D Roadmap," 2010.

from unregulated, poorly regulated, or inefficient fuel combustion, are the single most important man-made sources of air pollutant emissions, accounting for 85% of particulate matter and almost all sulfur oxide and nitrogen oxide emissions.⁴

In addition to air pollution, the growing accumulation of greenhouse gases in the atmosphere is increasing the risks associated with climate change. Figure 3 shows the projected change in global surface temperature, precipitation, and sea level over the next 100 years for two different emissions scenarios. The scenarios assessed by the Intergovernmental Panel on Climate Change report look at different trajectories of greenhouse emissions and atmospheric concentrations, air pollutant emissions, and land use out to the year 2100. The two scenarios shown in Figure 3 are: (1) a stringent mitigation scenario (RCP2.6), where the world makes a concerted effort to reduce emissions and (2) a scenario with very high greenhouse gas emissions (RCP8.5), where emissions continue to

rise throughout this century in the absence of climate policies.

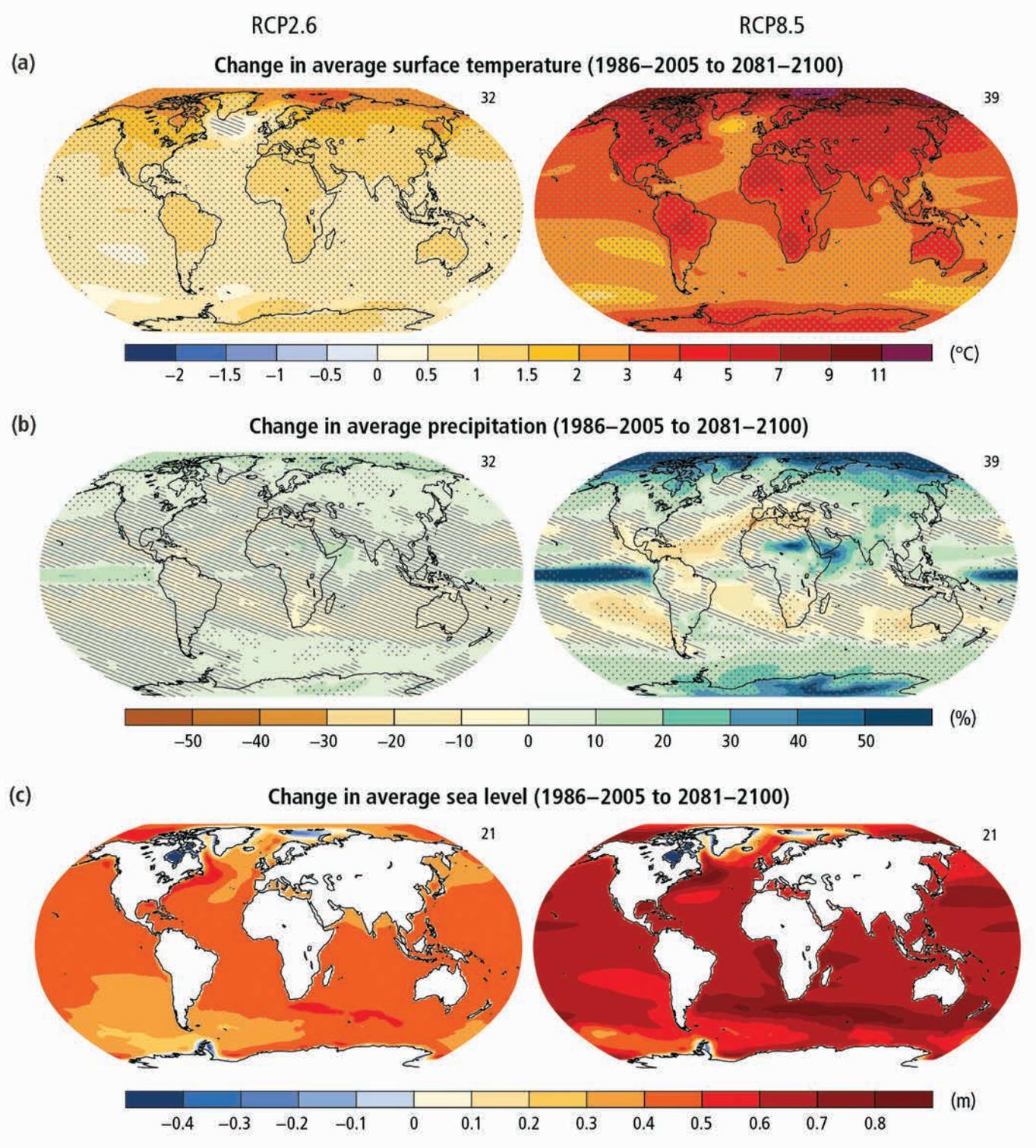
Just as the previous ice age—with temperatures only about 4–5 degrees Celsius colder than temperatures today—was a radically different climate, a warming of just a few degrees in the future would result in potentially serious consequences. As the U.S. National Academy of Sciences and The Royal Society⁵ describe:

Already, record high temperatures are on average significantly outpacing record low temperatures, wet areas are becoming wetter as dry areas are becoming drier, heavy rainstorms have become heavier, and snowpacks (an important source of freshwater for many regions) are decreasing. These impacts are expected to increase with greater warming and will threaten food production, freshwater supplies, coastal infrastructure, and especially the welfare of the huge population currently living in low-lying areas. Even though

⁴ IEA, World Energy Outlook Special Report, "Energy and Air Pollution," 2016.

⁵ The Royal Society and U.S. National Academy of Sciences, "Climate Change: Evidence and Causes," 2014. Available at: <http://dels.nas.edu/resources/static-assets/exec-office-other/climate-change-full.pdf>

FIGURE 3
Projected Changes in Global Surface Temperature, Precipitation, and Sea Level



Projected changes for a stringent reduction in greenhouse gases (left) and for unconstrained emissions (right).

Source: Intergovernmental Panel on Climate Change, "Climate Change 2014 Synthesis Report," Fifth Assessment Report, Figure 2.2.



© NASA

A global view of Earth at night. Many areas of the developing world are not yet electrified.

certain regions may realise some local benefit from the warming, the long-term consequences overall will be disruptive.

In 2015 at the Conference of Parties in Paris (COP21), 195 nations adopted a goal of limiting global warming to less than a 2-degree (Celsius) increase compared with pre-industrial levels. Working at odds with this goal, however, is the fact that some poorer countries may have abundant fossil fuel resources which provide the cheapest option to raise their populations' quality of life and lengthen average lifespans. As these countries are not likely to have the resources to develop clean energy technology options on their own, the Paris accords reflected a consensus opinion that wealthier nations, such as the United States, share a responsibility to help poorer nations develop cleaner options.

C. Nuclear Energy's Potential Role in Meeting Future Energy Demands

Given the current dominance of traditional fossil fuel energy use, limiting global warming to less than two degrees Celsius will require a transformation of the energy sector, relying on a broad portfolio of energy technologies.⁶ Energy efficiency will play a role in helping to reduce the demand for more energy, but new low-emission sources

of energy will be needed to replace existing fossil fuel sources.

Of the three broad types of low-emission energy technologies in the electricity sector—renewable, nuclear, and fossil with carbon capture and sequestration—only the second and third are dispatchable

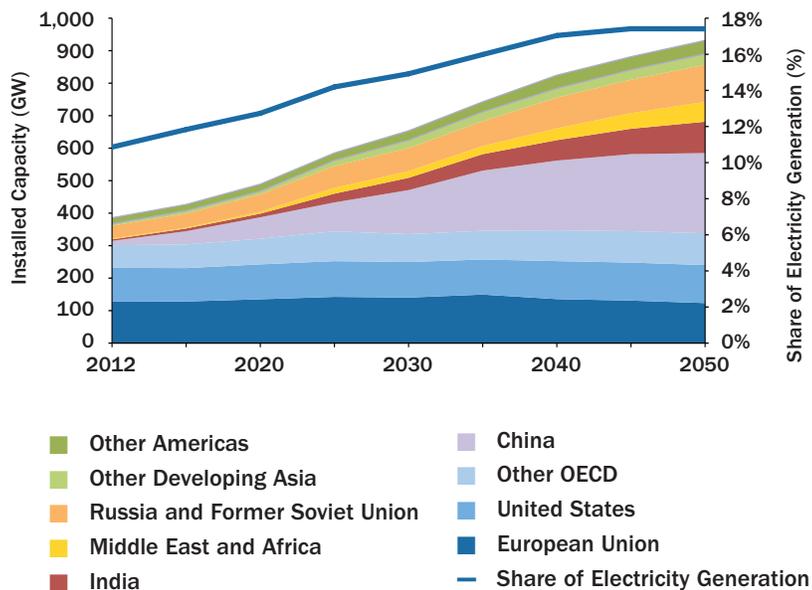
Limiting global warming to less than two degrees Celsius will require a transformation of the energy sector.

(e.g., can be dispatched at the request of power grid operators or plant owners). Between those two options, only nuclear energy is currently widely deployed, with decades of commercial experience.

The renewable energy technologies with the greatest potential for deployment—solar and wind—are dependent on the associated resources for a given location, which makes them more attractive in specific regions and countries, and less attractive in others. Wind and solar costs have fallen in response to innovation and deployment, the latter of which has been driven in part by electricity standards and tax incentives in the United States and elsewhere. As wind and solar technologies are still a small percentage of electricity generation,

⁶ See, for example, R. Socolow and S. Pacala, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, Vol. 305, pp. 968–972, 2004.

FIGURE 4
Projected Nuclear Energy Expansion to Limit Global Warming



IEA projection for nuclear energy deployment out to 2050 as part of a scenario to limit global warming to 2 degrees Celsius or less.

Source: © OECD/IEA and OECD/NEA, 2015 Technology Roadmap: Nuclear Energy, IEA Publishing. Licence: www.iea.org/t&c

their intermittency has not yet created a significant challenge for the operation of the U.S. electrical grid, which is composed largely of dispatchable energy sources that can, for example, keep the electrical grid operating when the wind dies down or the sun sets. But this could become a greater issue in the future as intermittent renewable energy increases its share of total generation.

Efforts to decarbonize the energy sector and reduce air pollution would be greatly aided by a global scale up in the use of nuclear energy. The IEA published a study, for example, which estimated that in order to limit global warming to less than two degrees, global nuclear capacity “would need to more than double from current levels of 396 GW to reach 930 GW in 2050.”⁷ The change in nuclear generating capacities by

region is illustrated in Figure 4. Some of the current 391 GW of nuclear generating capacity will also retire by 2050, adding to the number of new nuclear plants that must be built to reach 930 GW.

The EIA notes in its International Energy Outlook 2016 that “Long-term global prospects continue to improve for generation from renewable energy sources, natural gas, and nuclear power... After renewable energy sources, natural gas and nuclear power are the next fastest-growing sources of electricity generation.”⁸ EIA projects that worldwide nuclear generating capacity will reach 602 GW by 2040.

The remainder of this report focuses on one area of active U.S. nuclear energy development: SMRs. SMRs could serve multiple purposes for the United States: 1) keep the United States on the leading edge of nuclear energy development; 2) provide a new dispatchable clean energy option for the United States and the world to replace retiring fossil and nuclear generation; 3) create jobs through domestic builds and exports; and 4) help to ensure that the United States will be engaged in setting nonproliferation standards with countries developing new nuclear power programs over the coming decades.

Chapter II looks at the potential benefits of SMR deployment that argue for federal and state support. Chapter III examines the specific areas and conditions in the United States where SMRs are most attractive for deployment, while Chapter IV estimates international markets. Chapter V describes the national security rationale for supporting the development of nuclear power, especially power reactors such as SMRs. Finally, Chapter VI makes recommendations to the U.S. federal government and state legislatures.

The window for the United States to play a leadership role in the global nuclear energy regime and to guide the development of safety, security, and nonproliferation standards in other countries is limited and will eventually close. SMRs are one area where the United States still has the opportunity to lead—for the moment.

7 OECD/IEA and OECD/NEA, 2015 Technology Roadmap: Nuclear Energy. Available at: <https://www.iea.org/publications/freepublications/publication/technology-roadmap-nuclear-energy-2015-.html>

8 EIA, “International Energy Outlook 2016,” May 2016. Page 4.

CHAPTER II

THE SMALL MODULAR REACTOR OPTION

THE CURRENT U.S. NUCLEAR energy fleet is populated mostly by large light-water reactors with electrical outputs close to 1 GW. Economies of scale drove the U.S. industry towards these larger sizes, but the increases also led in some cases to greater complexity (e.g., added redundant safety and auxiliary systems), which in turn contributed to construction and operational challenges. The challenges seen in nuclear power plant construction in earlier decades,⁹ as well as the delays with nuclear plant projects today,¹⁰ argue for smaller reactors and a different approach to construction. The next generation of nuclear reactors that private companies have been working to develop and commercialize in recent years has tended to be smaller than these GW-scale reactors,¹¹ in part to take advantage of factory fabrication approaches and to allow for overland shipment of main reactor components and modules.

EPACT05 recognized SMRs in law by altering section 170 of the Atomic Energy Act of 1954, as amended. Section 608 (entitled “Treatment of Modular Reactors”) of EPACT05 defined “small” to be less than 300 MWe. In other words, the definition of SMRs in statute is independent of the type of coolant used by a given reactor design. Any nuclear power plant with modules meeting the cri-

teria described in EPACT05 can be treated as one reactor unit for the purposes of liability insurance. Early testimony¹² to Congress on SMR legislation also reflected this independence from the type of reactor coolant used, and emphasized that only

SMR concepts in this report include light-water and non-light-water designs

smaller reactors would be conducive to factory fabrication of reactor modules and transportation by rail or truck to a construction site.

For these same reasons, this report considers SMR designs utilizing all types of coolants. However, it must be acknowledged that in the intervening years, the most commonly used terminology has moved in a different direction. The DOE SMR Licensing and Technical Support (LTS) program has cost-shared light-water SMR design development, while R&D and cost-share work for non-light water-based designs has occurred in the DOE Advanced Reactor Technologies program. As a result, “SMR” has in some contexts become synonymous with “light-water SMR.” This report, however, does not use the term “SMR” in that way.

SMR concepts in this report include light-water designs,¹³ and high temperature gas reactors

9 See, for example, the history in D. Ingersoll, “Deliberately small reactors and the second nuclear era,” *Progress in Nuclear Energy* 51 (2009), 589–603.

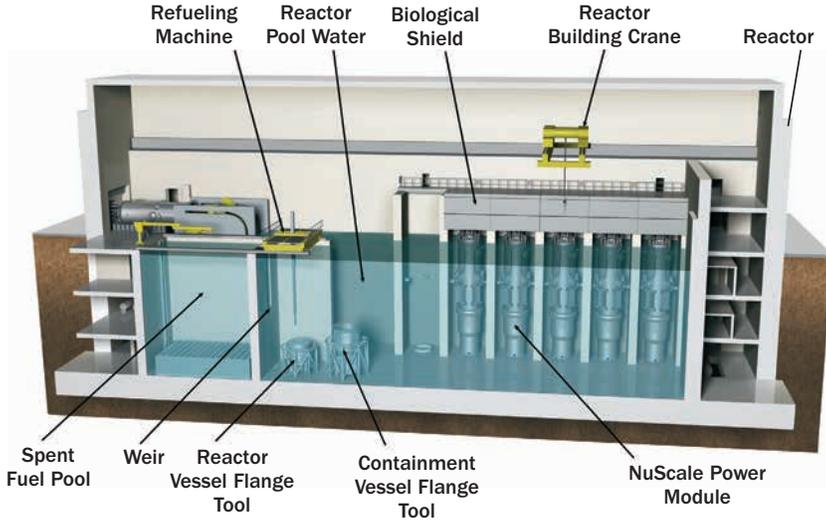
10 https://www.nytimes.com/2017/03/29/business/westinghouse-toshiba-nuclear-bankruptcy.html?_r=0

11 <http://www.thirdway.org/report/the-advanced-nuclear-industry>

12 Testimony of Warren F. Miller, Jr., Assistant Secretary for Nuclear Energy, December 15, 2009 to the Senate Energy and Natural Resources Committee.

13 For instance, NuScale is designing a 50 MWe reactor module. It received \$217 million from the Department of Energy and at the end of 2016, submitted the first design certification application to the U.S. Nuclear Regulatory Commission for an SMR design. A cut-away view of the NuScale Power reactor building is shown in Figure 5

FIGURE 5
Cut-Away View of the NuScale Power Reactor Building

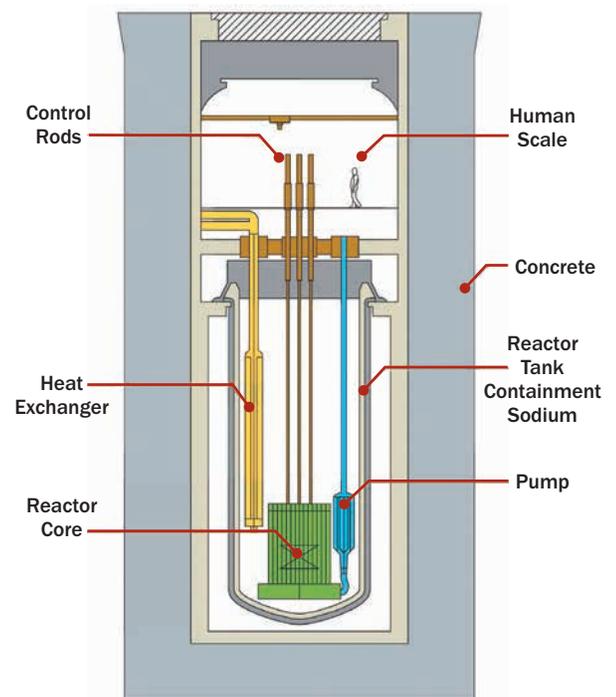


Source: © NuScale Power, LLC

(HTGRs),¹⁴ fast reactors,¹⁵ molten salt reactors,¹⁶ and nuclear generator concepts.¹⁷ The range of SMR designs in development have very different technical considerations and associated challenges, and individual concepts are targeting different markets. All of them, however, could advance the U.S. nuclear industry in important ways.

By virtue of their size, SMRs should enable shorter construction periods compared with larger nuclear power plants. Their size also enables the possibility of factory fabrication for reactor modules, which could further reduce construction schedule times, as well as costs. Gigawatt-scale reactor modules, independent of coolant, are too large to fabricate in a factory setting and transport to a power plant site. Smaller reactors also mean lower overall capital costs, which reduces the financial risks to the entities involved in their construction. Finally, the range of SMR designs offer several other potential advancements in nuclear energy, including new standards for passive nuclear safety, better integration with renewable energy sources, and process heat applications.

FIGURE 6
Advanced Reactor Concepts' ARC-100 Power Module



Source: © Advanced Reactor Concepts, LLC

A. Lower Capital Costs, Simplified Designs, and Shorter Construction Times

The U.S. shipbuilding industry provides an example of sector where modular construction techniques have created a faster and more efficient construction process. In the building of submarines and aircraft carriers, techniques evolved over time towards modular construction where more work was done away from the eventual construction site. These potential cost savings have not yet been proven, however, for nuclear power plant construction in the United States, though participants in the shipbuilding industry have indicated that SMRs lend themselves to learning effects that could bring costs down.¹⁸

SMR companies plan to develop modularized components that are fabricated in a manufacturing facility and assembled at the power plant site. The

14 X-energy recently received a \$40 million award from the DOE to develop its HTGR design, shown in Figure 8.

15 The ARC-100 is a 100 MWe sodium-cooled fast reactor, shown in Figure 6.

16 Terrestrial Energy is pursuing an integral molten salt reactor design, shown in Figure 9.

17 For example, Oklo is working on a 2 MWe compact fast reactor.

18 See Appendix C of the 2011 University of Chicago study, "Small Modular Reactors—Key to Future Nuclear Power Generation in the U.S." Excerpt: "Both General Dynamics and Northrup Grumman, the two leading Navy shipbuilding contractors, have assessed the SMR technologies and indicate that the designs lend themselves to similar learning effects."

smaller plant size and simpler design mean that the components are correspondingly smaller, thus easier to make or available off the shelf, and there are fewer safety-grade components requiring increased manufacturing specialization. Indeed, one of the major rationalizations for SMRs is that the reactor modules are small enough to be factory built and transported to the plant site by ship, rail, or truck, as depicted in Figure 7. Basing SMR factories in the United States for export to other areas of the world could create thousands of U.S. jobs, as discussed in Chapter IV: Global SMR Market Studies.

Larger nuclear plants have greater financial risk involved in their construction. Schedule delays and cost overruns for larger projects have correspondingly greater impact than those associated with smaller projects. SMRs enable utilities to buy a smaller piece of nuclear power and thus take on less risk in terms of overall capital at stake. Where a large plant may cost \$12–15 billion and take five years or more to construct, an SMR may cost \$2–3 billion (or substantially less), and may be built in four years or less.

B. New Standards for Passive Nuclear Energy Safety

Advancing safety and increasing safety margins are priorities for every new generation of nuclear reactor designs. The accident at Japan's Fukushima Daiichi on March 11, 2011 illustrated how reactors that do not need off-site electricity, off-site water, or operator intervention would provide safety advantages. Achieving these types of robust safety characteristics is generally easier for smaller reactors due to the lower total heat produced in a smaller reactor core. In this way, SMR designs could set a new standard for passive nuclear energy safety in the U.S. commercial nuclear fleet.

For example, the use of natural circulation in some light-water SMR designs allows for the elimination of traditional components, such as reactor coolant pumps. Eliminating reactor coolant pumps means that off-site electricity is not required to continue cooling the fuel rods in the event of an accident. Light-water SMRs also have a smaller amount of nuclear material on-site compared with the larger LWRs and thus a smaller source term.

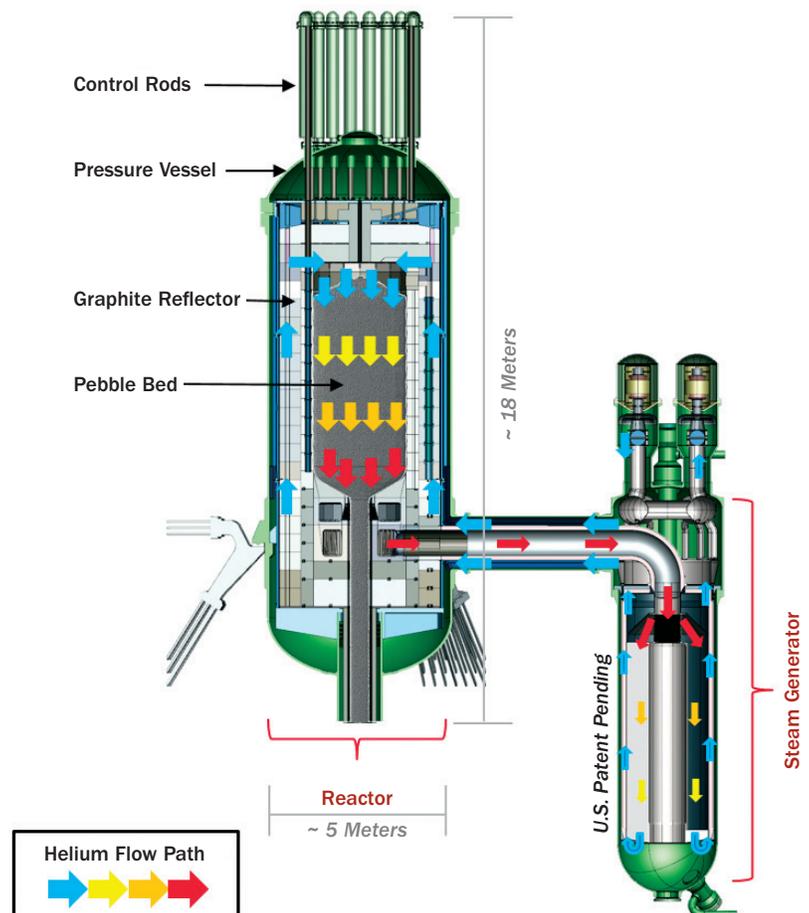
Alternative fuel forms, such as the particle-based fuel used in HTGRs, have higher melting temperatures than conventional light-water reactor fuels. The multiple barriers to the release of radioactive material in particle-based fuels include layers

FIGURE 7
Artist's Conception of Shipping an SMR Module by Barge



Source: © NuScale Power, LLC

FIGURE 8
X-energy's Xe-100 Power Module



Source: © X-energy, LLC

FIGURE 9
 Terrestrial Energy's Integral Molten Salt Reactor Power Plant Layout



Source: © CC-BY-SA

of ceramic coatings on the nuclear fuel, the carbon encasement, and the graphite core structure.¹⁹ These design innovations mean that fuel melting and radiation release is ruled out in postulated accident conditions, leading to power plants with very long to unlimited coping times. One HTGR design, the Xe-100, is shown in Figure 8.

Liquid-metal-cooled designs, such as the sodium fast reactor ARC-100 (shown in Figure 6), contain coolants with much greater effectiveness at heat transfer than water-cooled designs. Their low-pressure operation and significant margins to boiling also mitigate loss of coolant concerns, as well as the need for coolant injection systems. The experiments performed at EBR-II demonstrated that for those design parameters, as temperature increases and materials expand, a net negative reactivity feedback leads to inherent safety responses.²⁰ In this full-scale reactor test, it was demonstrated that without any coolant flow and with control rods

out of the core, the reactor would shut itself down naturally without any fuel damage, due to this negative temperature reactivity feedback.

Molten salt reactor concepts, such as Terrestrial Energy's (shown in Figure 9) have a unique solution to the challenge of cooling, containing, and controlling a nuclear reactor. By design, the fuel is already liquid and has natural characteristics that cause the coolant temperature to increase when heat extraction in the steam generator is reduced, which inherently and naturally lowers reactor power. The opposite effect occurs when heat extraction is increased: the coolant temperature drops and reactor power increases. Any malfunction or accident that causes the reactor core and liquid fuel to heat up—such as loss of core cooling, or loss of heat sink, or station black out—would result in the reactor reducing power, due to these inherent characteristics of the liquid fuel. Several molten salt reactor concepts rely on a freeze valve at the bottom

19 See the graphics at <http://www.x-energy.com/copy-of-xe-100-reactor> for an illustration of the multiple barriers for pebble fuel.

20 See a presentation by Bob Hill at: https://www.gen-4.org/gif/upload/docs/application/pdf/2016-12/geniv_sfr_bobhill_final.pdf

of the reactor core to melt upon loss of power, thus draining the liquid fuel to a separate tank and shutting down the nuclear fission process. Others, such as the Terrestrial Energy design, rely on the natural characteristics of the liquid fuel as described above to reduce power, where the reactor is then passively cooled for an indefinite period without need for draining the liquid fuel to a separate tank. Thus, even if the operators are no longer on site, it is possible for a molten salt reactor to passively reduce power and enter a safe state on its own.

C. Better Integration with Renewable Energy Sources

Increased consumer demand, declining costs, state renewable portfolio standards,²¹ and state and federal renewable energy tax credits²² have driven intermittent renewable energy generation to 6.5% (0.9% solar and 5.6% wind) of total U.S. electrical generation in 2016.²³ These same drivers are expected to continue and increase the portion of intermittent renewable energy in the U.S. electrical grid. This has already brought benefits in the form of reduced air pollution and greenhouse gas emission, as well as others. However, much greater penetration of the grid by intermittent renewable energy will bring new grid management challenges. As the Electric Power Research Institute (EPRI) has noted:

“Because variable renewable resources don’t have full capacity at all times, they don’t contribute to fulfilling capacity requirements in the same way that a thermal generator does... As these variable or energy-limited resources become more common, system planners are presented with an increasingly complex task of blending the unique characteristics of these resources in planning for future capacity needs. Otherwise, the system may become overbuilt and expensive, or underbuilt and prone to costly service interruptions.”

The current low price of natural gas (see Figure 17 in Chapter IV) has led to an increase in natural

gas plant deployment, which can also be used to back up intermittent renewable energy generation. An increased dependency on natural gas plants, however, has its own drawbacks.

The North American Electric Reliability Corporation (NERC) examined the risks of high grid penetration of natural gas-fired generation and the associated operational challenges²⁴ and stated that it “...continues to assess the increasing risk of fuel disruption impacts on generator availability from the dependency of electric generation and natural gas infrastructure.”

For example, the polar vortex event in 2014²⁵ showed the weather dependency and associated vulnerability of an increased use of natural gas for electricity generation. The extremely cold weather in the Midwest, South Central, and East Coast regions of North America that year increased the demand for natural gas for heating purposes, which resulted in a significant amount of gas-fired electricity generation being unavailable (due to curtailments).

A different kind of vulnerability from increased use of natural gas was illustrated in 2015 when the largest methane leak from a natural gas storage facility in U.S. history was discovered by Southern California Gas Company within its Aliso Canyon Storage Field.²⁶ Approximately 90,000 metric tons of methane—a greenhouse gas with 25 times the global warming potential compared with carbon dioxide over a 100-year time horizon—was released from the well. The leak led to evacuations and health impacts on the nearby community.

Recently, the Western Electricity Coordinating Council (WECC) observed that over the next 10 years, between 4,000 and 6,000 MW of western coal plants are anticipated to retire, while new capacity additions over the past 20 years have been mostly natural gas plants and variable energy resources, such as wind and solar. WECC noted that fuel security is thus declining, given that nearly 40% of the resource mix is now hydro, wind, or solar, which are susceptible to longer- and shorter-term

21 For a list of state measures, see: <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>

22 <http://www.dsireusa.org> shows both state and Federal tax incentives available on a state-by-state basis

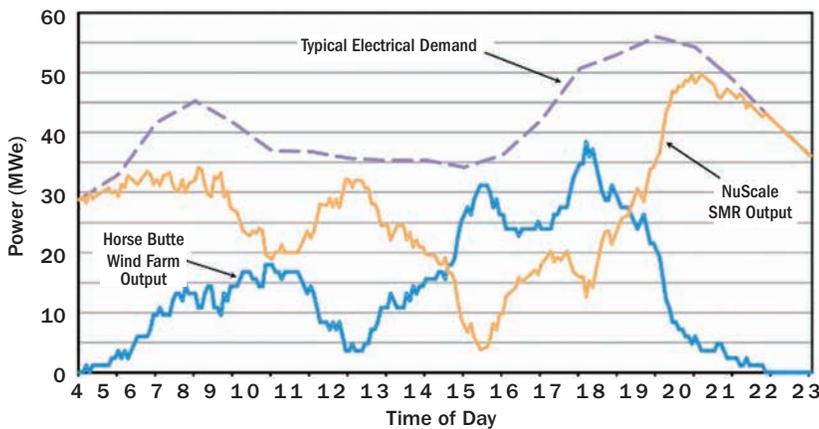
23 Data from EIA-923 survey form, December 2016. Available at: <https://www.eia.gov/electricity/data/eia923>

24 NERC, “Short-Term Special Assessment: Operational Risk Assessment with High Penetration of Natural Gas-Fired Generation,” May 2016

25 NERC, “Polar Vortex Review,” September 2014.

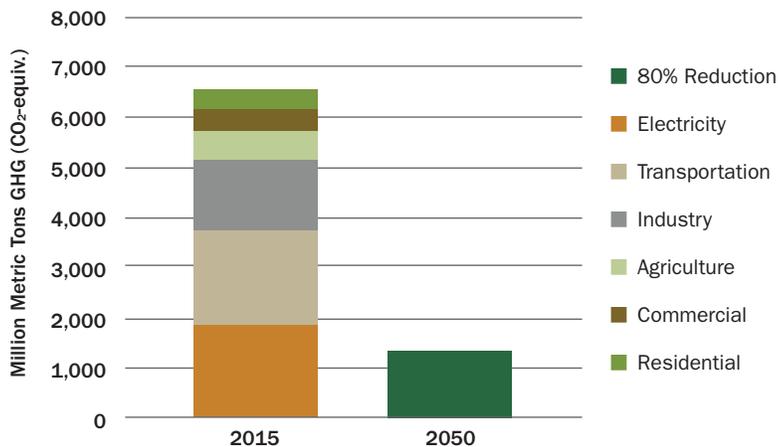
26 The Interagency Task Force on Natural Gas Storage Safety, “Ensuring Safe and Reliable Underground Natural Gas Storage,” Final report, October 2016.

FIGURE 10
Balancing the Electrical Output of a Wind Farm with an SMR



Source: Ingersoll et al, "Can Nuclear Power and Renewables be Friends?" Proceedings of ICAPP 2015, May 3–6, 2015.

FIGURE 11
2015 U.S. Greenhouse Gas Emissions by Sector with an 80% Reduction Shown for Scale



Source: EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks," 2017. Table ES-6.

weather patterns, and another 40% of capacity is natural gas, which is also susceptible to weather-related interruptions.²⁷

For these reasons, adding SMRs to a generation portfolio of intermittent renewable energy and natural gas plants would provide several grid reliability benefits to the United States.

First, SMRs have at least two years (and in some

cases several decades) of fuel on site. As a result, they are not subject to the kinds of short-notice fuel disruptions (e.g., polar vortex-type events) that affect natural gas plants. Also, fuel prices for SMRs are not changing on a weekly or monthly basis during operation, as they may with NGCC plants, which can lead to economic disruptions.

Second, with the much greater proportion of intermittent energy on the electrical grid, there is an increased need to replace older dispatchable power sources as they retire, to maintain grid stability and meet rising peak demand. Some SMRs, by virtue of their smaller size and other operational features, have a greater capability to conduct load-following operations than larger nuclear power plants. As Figure 10 shows, an SMR could be coupled with an intermittent source of renewable energy, such as a wind farm, to meet the typical daily rise and fall in electricity demand.

D. Process Heat Applications

Another important feature of SMRs is the potential to provide heat for non-electricity missions, enabling nuclear energy to help decarbonize the transportation, industrial, commercial, and residential sectors.²⁸ Some process heat applications utilize temperatures in the range of light water reactor outlet temperatures, while others require process heat at greater temperatures and would require switching to a different coolant technology, such as gas, liquid metal, or molten salt.²⁹

While existing U.S. nuclear reactors are only used to produce electricity, reactors in other countries have carried out non-electricity missions such as district heating and desalination. As Figure 11 shows, most U.S. greenhouse gas emissions come from outside the electricity sector and the traditional use of fossil fuels in other sectors will have to be replaced by other low-emission sources of power to achieve large reductions in greenhouse gas emissions. Even if the U.S. electricity sector was fully decarbonized by 2050, that by itself would still fail to achieve an 80% reduction in total greenhouse gas emissions by a large margin.

The size of SMRs and the option to deploy them as multiple independent modules make them

²⁷ Comments to the DOE Quadrennial Energy Review, Jim Robb, WECC CEO. Available at: [https://energy.gov/sites/prod/files/2016/04/f30/Panel%201%20Remarks%20by%20Jim%20Robb,%20Chief%20Executive%20Officer%20Western%20Electricity%20Coordinating%20Council%20\(WECC\).pdf](https://energy.gov/sites/prod/files/2016/04/f30/Panel%201%20Remarks%20by%20Jim%20Robb,%20Chief%20Executive%20Officer%20Western%20Electricity%20Coordinating%20Council%20(WECC).pdf)

²⁸ See a 2016 report by the Joint Institute for Strategic Energy Analysis, "Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions" for an analysis of greenhouse gas emissions from the industrial sector and the possibility to displace these emissions using SMR, solar, and geothermal energy technologies.

particularly well suited to carry out several non-electricity missions.

Water desalination using nuclear power plants has been demonstrated as an option in other countries to meet growing demand for potable water. Clean water is essential for global development, though clean drinking water is out of reach for as much as one fifth of the world's population. Several countries have implemented nuclear desalination, including Kazakhstan, which operated a 750-megawatt nuclear thermal facility for more than a quarter century, generating not only desalinated water, but process heat and electricity as well.³⁰ More than 200 reactor years of operating experience have been reached worldwide, and demonstration projects for nuclear desalination are in progress to confirm its technical and economic viability. However, today nuclear desalination contributes only 0.1% of total desalting capacity worldwide.³¹ SMR operational flexibility provides the opportunity for water production to take place during off-peak hours of the day, when demand for electricity is lower.

District heating has also been demonstrated using nuclear power plants connected with a network of distribution and return pipes to heat residential homes and provide hot water. It is more often used in climatic zones with long and cold winters. Russia, for example, has the most extensive experience in using nuclear energy to run heating grids of towns with typically 50,000 inhabitants, situated 3km to 15km from the closest power plants.³²

Transportation fuel production using nuclear energy would help to reduce carbon emissions from the transportation sector. The production of refined petroleum products is highly energy intensive with most of the energy used either in the field for crude oil recovery processes or at a refinery for processing the crude oil into end-use products such as transportation fuels or petrochemicals. Over the past decade, roughly 7% of the total U.S. energy consumption has taken place at oil refineries, which equates to an average power demand of 200 GW.

Older refineries can consume up to 15–20% of the energy value of their feedstock to supply process heat, but modern refineries average closer to 6% and use almost entirely natural gas feedstock or refinery fuel gas to produce the required heat.³³

SMRs could help to set a new standard for passive nuclear energy safety in the United States, and improve electrical grid reliability in an era of increasing intermittent renewable energy deployment.

Hydrogen production around the world is estimated to represent about 2% of the world's total energy consumption, and is expected to grow 4-10% per year.³⁴ Hydrogen is used in the fertilizer industry for the manufacture of ammonia, for the refining of petroleum products, and could potentially be used extensively as a transportation fuel. Using SMRs as a source of process heat in hydrogen production, as opposed to fossil fuels, would reduce the carbon emissions associated with this commodity.

These process heat missions raise the possibility of constructing nuclear-renewable energy hybrid systems that create one or more energy commodities. These coupled systems could be used to provide load-following electrical power to match diurnal to seasonal-scale changes in power demand or to compensate for the variability of wind or solar generation.³⁵ Figure 12 depicts how SMRs could function as part of such a hybrid energy system. When wind and PV solar plants are producing larger amounts of electricity, an SMR could switch from electricity generation to process heat applications, such as hydrogen production or desalination.

The small size and simplified designs for SMRs, along with the potential for factory fabrication of reactor modules, should increase the likelihood that

29 Page 25 of DOE's Nuclear Energy Research and Development Roadmap, April 2010.

30 See <https://www.nei.org/Knowledge-Center/Other-Nuclear-Energy-Applications/Water-Desalination>; accessed on August 17, 2017.

31 "Advanced Applications of Water Cooled Nuclear Power Plants," International Atomic Energy Agency, IAEA-TECDOC-1584, July 2007.

32 *ibid.*

33 Ingersoll et al, "Extending Nuclear Energy to Non-Electrical Applications," Proceedings of the 19th Pacific Basin Nuclear Conference, August 24–28, 2014.

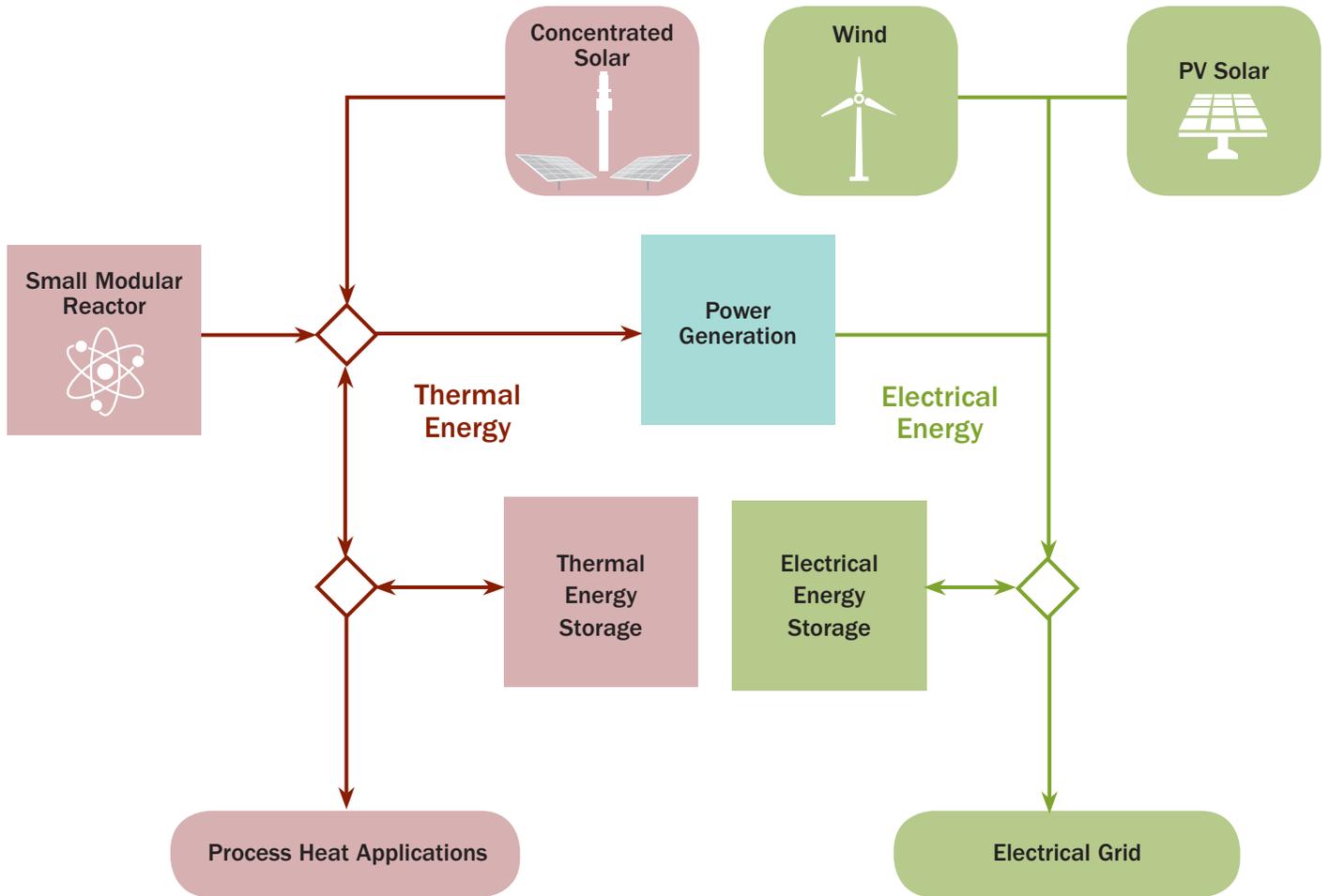
34 IAEA, "Hydrogen Production Using Nuclear Energy," 2013.

35 Joint Institute for Strategic Energy Analysis, "Summary Report of the INL-JISEA Workshop on Nuclear Hybrid Energy Systems," 2012. Available at: <http://www.nrel.gov/docs/fy12osti/55650.pdf>

SMR construction is completed in a shorter amount of time compared with the large light-water reactors. Moreover, SMRs could help to set a new standard for passive nuclear energy safety in the United States, and improve electrical grid reliability in an era of increasing intermittent renewable energy deployment. The process heat applications for SMRs could create a new way for nuclear energy

to contribute to U.S. energy and environmental goals, potentially as part of hybrid energy systems that make use of SMRs' flexible mission capabilities. The next two chapters examine where SMRs are most attractive for deployment in the United States, and what might be the size of the international market for SMRs.

FIGURE 12
Hybrid Energy Systems with SMRs, Solar Plants, and Wind Power



Source: Idaho National Laboratory has created similar hybrid energy system graphics. See, for example, slide 10 of a presentation by Shannon Bragg-Sitton and Richard Boardman, "Integrated Nuclear Renewable Energy Systems Development," given to the IAEA Flexible Operations Technical Meeting on October 7, 2014.

CHAPTER III

WHERE SMRS ARE MOST ATTRACTIVE IN THE UNITED STATES

COMPARISONS OF ENERGY generation technologies are commonly shown as a chart depicting the LCOE³⁶ for each energy technology. LCOE is one way of comparing the value of generation sources, though not the only factor that utilities consider.³⁷ For example, as the EIA acknowledges, the value proposition between a dispatchable power plant and an intermittent generator is not equal.³⁸

The LCOE of an SMR versus other generation technologies, however, varies considerably within the United States. Renewable technologies have an obvious geographic dependency on the available resources for a given location—a solar facility in Arizona produces energy at a very different cost than the same facility in Alaska. Furthermore, the full value proposition of a solar generator may vary by geography for reasons distinct from LCOE. A solar facility in Arizona may help contribute to meeting peak demand, as peak demand will come during the day and during the summer, but a similar solar facility may not be particularly helpful with meeting peak energy demand during the cold and dark winters of Alaska. Even the price of natural gas varies somewhat from state to state.³⁹

The state regulatory environment and the financing structure used by the entity building a new generation asset also affect the appeal of nuclear power versus other generation technologies. In most cases, the principal comparison for new nuclear plants is with NGCC plants, given the low price of natural gas in recent years. As discussed below, however, a utility may want to avoid an over-dependence on natural gas plants given the volatility of natural gas prices as well as the uncertainty over their long-term future.

A. State-by-State Differences

State laws and regulations regarding energy production vary widely; it is thus difficult to adequately explore in this report the nuances of energy policy in all 50 states. One obvious difference, specific to nuclear plants, is that some states have laws in place that either ban new nuclear plant construction outright or require that it be subject to voter or legislative approval, or other requirements. Fourteen states have placed restrictions on the construction of new nuclear power facilities: California, Connecticut, Hawaii, Illinois, Maine, Massachusetts, Minnesota, Montana, New Jersey,

36 Page 5–3 of the 2004 University of Chicago study, “The Economic Future of Nuclear Power,” states: “...levelized cost of electricity, or LCOE, is defined as the constant real price of electricity over the life of the plant that compensates debt and equity investors at their required rates of return.”

37 Another illustration can be found in 2011 discussion draft by Paul Joskow, “Comparing the costs of intermittent and dispatchable electricity generating technologies,” that begins on page 16 with, “Let us use an extremely simple characterization of an electric power system to illustrate why comparing levelized costs for dispatchable and intermittent technologies like wind and solar provides little if any insight into their comparative economic values.” The paper is available at: <https://economics.mit.edu/files/6317>

38 EIA Electricity Generation 2016, “The duty cycle for intermittent renewable resources, wind and solar, is not operator controlled, but dependent on the weather or solar cycle (that is, sunrise/sunset) and so will not necessarily correspond to operator dispatched duty cycles. As a result, their LCOE values are not directly comparable to those for other technologies (even where the average annual capacity factor may be similar) and therefore are shown in separate sections within each of the tables.”

39 EIA records these differences at: https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_a.htm

New York, Oregon, Rhode Island, Vermont, and West Virginia.⁴⁰

A second consideration is whether a state has a more traditional rate-regulated electricity market or a deregulated market structure.⁴¹ In deregulated states, the public utility commissions do not set the retail price of electricity themselves; rather, the price of electricity is heavily influenced by the wholesale price resulting from markets managed by a regional transmission organization. The wholesale

The Southeast in particular, along with parts of the Mountain West, Southwest, and Midwest, appear to be the best areas for new nuclear power deployment based solely on consideration of state laws and regulations, though other factors are also important.

price of electricity can change over several orders of magnitude and can even be negative.⁴² In the markets operated by regional transmission organizations, the highest accepted bid for a given time period determines the price of electricity that all generators will receive at that time. This means that when private companies in deregulated states are deciding what new generation to build, they must contend with substantial uncertainty over what the price of electricity will be over the lifetime of their proposed plants. That uncertainty combined with the current low price of natural gas strongly discourages the construction of nuclear power plants, which are capital intensive and have longer construction cycles.

California, Connecticut, Delaware, Illinois, Massachusetts, Maryland, Maine, Michigan, Montana, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Texas, and the

District of Columbia have deregulated market structures.⁴³ In 2016, 41% of electricity generation in the United States came from power plants in these states and the District of Columbia.⁴⁴

A third difference is that regulated states can be further divided into those that use ‘allowance for funds used during construction’ (AFUDC) accounting and those that permit utilities to charge the allowed rate of return on ‘construction work in progress’ (CWIP).⁴⁵ In states with AFUDC accounting, the utilities are not allowed to include the cost of construction or the interest accrued during construction in the rate base until the plant is in operation. This means that utilities bear all of the risk of construction completion, and as a result, investment banks tend to require a higher rate of return for electricity generating projects being built under AFUDC regulation than for projects in CWIP states. AFUDC accounting also means that rate jumps are higher when projects come online and the projects themselves are somewhat more expensive (a few percent higher) due to the accrual of interest on interest during construction.

Figure 13 depicts these state-by-state variations. The dark green states are regulated and use CWIP accounting and most have no restrictions on new nuclear plant builds. For the reasons noted above, these are nominally the best states for new reactors, though other factors, such as growth in electricity demand, public support for nuclear power, etc., are also important. Figure 13 shows that the Southeast in particular, along with parts of the Mountain West, Southwest, and Midwest, appear to be the best areas for new nuclear power deployment.

The remainder of this chapter considers three categories of entities in the United States that build power plants: merchant plant owners in deregulated states, investor-owned utilities (IOUs) in regulated states, and public power entities.

Merchant plant owners in deregulated states. In fully deregulated states, a power generation

40 The National Conference of State Legislatures provides a list: <http://www.ncsl.org/research/environment-and-natural-resources/states-restrictions-on-new-nuclear-power-facility.aspx>; accessed on 8-7-17.

41 The American Public Power Association, in its “Retail Electric Rates in Deregulated and Regulated States: 2015 Update” report, describes it thusly: “The deregulated category includes states with retail choice programs, and whose rates are strongly influenced by wholesale power prices in markets under the jurisdiction of the Federal Energy Regulatory Commission (FERC). These states allow end-use customers to choose their electricity provider (retail choice) and no longer have rate caps or other forms of regulatory protections that limit customers’ exposure to wholesale market prices.”

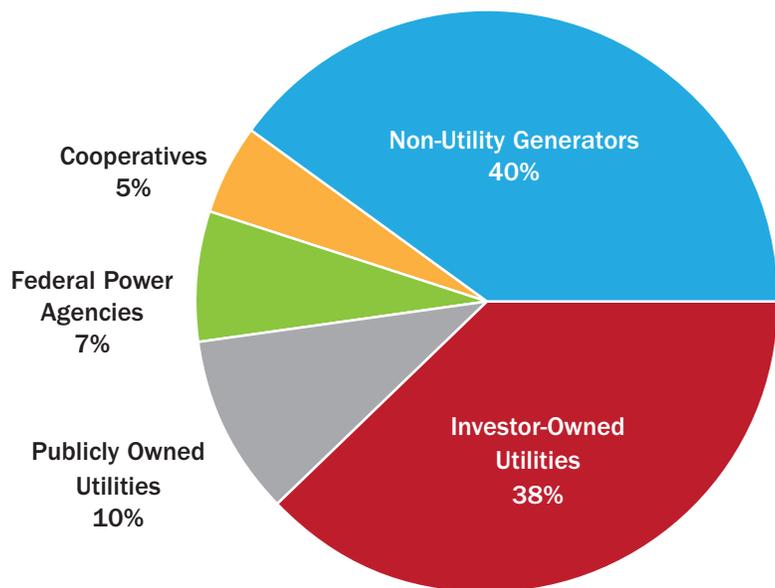
42 EIA, “Negative prices in wholesale electricity markets indicate supply inflexibilities,” February 23, 2012. Available at: <https://www.eia.gov/todayinenergy/detail.php?id=5110>

43 See page 2 of the American Public Power Association’s “Retail Electric Rates in Deregulated and Regulated States: 2016 Update.”

44 Data from EIA-923 survey form, 2016.

45 G. Rothwell, “The Economics of Future Nuclear Power,” Routledge, 2016. See Section 2.3 and Table 2.6.

FIGURE 14
2014 U.S. Electricity Generation by Ownership



Source: American Public Power Association, "U.S. Electric Utility Industry Statistics," 2014

their electricity prices and thus recover their costs with greater certainty. But unlike merchant companies, IOUs are prohibited from making over a certain rate of profit on their investments. Electricity prices in regulated states have historically been lower than those in deregulated states.⁴⁷

Public power entities. Non-profits or "public power" entities generate close to 22% of U.S. electricity. Municipal entities, state political subdivisions, rural electric cooperatives, and federal utilities, such as TVA, are not in the business of electricity generation to make a profit. Projects are executed on an at-cost basis, using 100% debt. To build a new power plant, a public power entity will take out a loan from a bank or other lender (or sell a bond) and charge its customers only what is needed to pay

the corresponding debt or interest payments. Given that public power entities are tax-exempt and in many cases local governments, they typically access lower rates of debt than investor-owned utilities or companies in merchant markets.

As Figure 14 shows, electric cooperatives generate nearly 5% of the total electricity produced in the United States every year⁴⁸ and publicly-owned utilities generate around 10% of U.S. electricity.⁴⁹ Currently more than 2,000 municipal utilities and almost 900 cooperative utilities operate in the United States. Federally owned power generation, such as that owned by TVA, contributes another 6.6%. Public power entities own 18.5 GW of the 99.6 GW of nuclear generating capacity in the United States.⁵⁰

It is no coincidence that the two early site movers for SMRs are public power entities that take a longer view on the value of electricity generation assets than investors in deregulated markets looking to make near-term profits on their investments. For example, UAMPS has worked with DOE to attain a site use permit at the Idaho National Laboratory (INL) to potentially operate an SMR for 100 years.⁵¹ Another DOE SMR utility partner, TVA,⁵² has submitted an early site permit application to potentially build multiple SMR units at the Clinch River Site in Oak Ridge, Tennessee. The application was accepted and docketed by the U.S. Nuclear Regulatory Commission (NRC) in January 2017.⁵³

Public power entities own aging coal and nuclear plants and are understandably concerned about what will replace these plants when they retire. Coal plants are facing air pollution reduction requirements, and potential restrictions or costs related to greenhouse gas emissions. Natural gas plants are an obvious replacement choice, though utilities would prefer not to be overly dependent on a single fuel source and, thus, vulnerable to volatility in natural gas prices.

47 American Public Power Association, "2014 Retail Electric Rates in Deregulated and Regulated States," 2015.

48 National Rural Electric Cooperative Association, "America's Electric Cooperatives: 2017 Fact Sheet," January 31, 2017. Available at: <http://www.electric.coop/electric-cooperative-fact-sheet>; Accessed August 17, 2017.

49 American Public Power Association, "U.S. Electric Utility Industry Statistics, 2014," page 56.

50 Data from: <https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Operators,-Owners-and-Holding-Companies>

51 The text for the DOE-UAMPS use permit can be found at: http://www.id.energy.gov/insideNEID/PDF/DOE_UAMPS%20Use%20Permit%20DE-N700065.pdf

52 In 2016, TVA began commercial operations at the Watts Bar 2 site, which was the first new U.S. nuclear plant to begin producing electricity in 20 years. Press release: <https://www.tva.gov/Newsroom/Watts-Bar-2-Project>

53 See TVA announcement at: <https://www.tva.gov/Energy/Technology-Innovation/TVA-Clears-Next-Hurdle-for-Small-Modular-Reactors>

TABLE 1
SMR and NGCC Plant LCOE for Three Types of Ownership
 (All numbers in cents/kWh using 2016\$)

Plant Type	Merchant company in a deregulated state	Investor owned utility in a regulated state	Public power entity	Public power entity with a \$25/tonCO ₂ charge
SMR	14	10	6.1	6.1
NGCC	5.9	5.3	4.6	5.5

B. Levelized Cost of Electricity for SMRs Compared with NGCC Plants

This report assumes that the building of new coal plants in the United States is unlikely for reasons of air pollution regulation and greenhouse gas emission concerns, which will remain in place or increase for the foreseeable future. Thus, the main dispatchable competition for new nuclear power plant construction is new natural gas plant construction. Natural gas plants are in some ways the inverse of nuclear plants: they are not capital-intensive, most of their generation cost comes from the fuel, and their fuel is subject to substantial price swings. From a climate perspective, the United States cannot achieve deep greenhouse gas emissions reductions by solely replacing retiring coal and nuclear plants with NGCC plants. Although they do not produce as much carbon dioxide as coal plants, natural gas plants still generate large amounts of greenhouse gases. In addition, the cost of NGCC plants comes mostly from the natural gas, so from a local community's perspective, the money spent to produce electricity from NGCC plants may not be a good investment since it mostly goes outside the local region. In contrast, since the fuel cost of nuclear is low, the money spent operating an SMR goes to salaries and non-fuel materials and services: more of it is retained in the local region.⁵⁴

Table 1 shows estimates for the LCOE of SMRs versus NGCC plants depending on the type of ownership. The estimates shown do not include first-of-a-kind costs for either source of generation.⁵⁵ Table 1 illustrates that SMRs are a much less attractive proposition than NGCC plants in deregulated states, but are more attractive in other states, and

especially for public power entities that are providing electricity on an at-cost basis.

Applying a modest price (\$25/tonCO₂) on carbon dioxide emissions, as shown in Table 1, SMRs can be roughly competitive with NGCC for public power entities at anticipated natural gas prices in the coming decades, and learning curves and factory fabrication could improve this comparison further.⁵⁶ Loan guarantees from the U.S. Department of Energy⁵⁷ would help investor-owned utilities in regulated states, and potentially some public power entities, access debt at lower rates and further improve the economic competitiveness of SMRs compared to NGCC plants. As the next section explores, the stability of nuclear plant generating costs⁵⁸ provides an additional reason for utilities to consider adding SMRs to their generation portfolios.

C. Reducing Utility Exposure to Natural Gas Price Volatility

A defining trend in the electricity sector in recent years has been the fall in natural gas prices. No other electricity generation source, including renewable energy technologies, has been able to compete with new natural gas plants in terms of total value. (Notably, solar and wind technologies have not had to directly compete with new NGCC plants in some cases, due to state renewable portfolio standards, as well as state and federal financial incentives.)

The EIA's Annual Energy Outlook 2017 projects that natural gas prices will increase to \$4.64/mmBtu in 2026 and ultimately to \$5.83/mmBtu in 2050. However, as shown in Figure 15, natural

54 See, for example, slide 5 of <http://files.constantcontact.com/14bf1850201/249506b2-cebf-46f1-9423-9c5c70096acd.pdf>

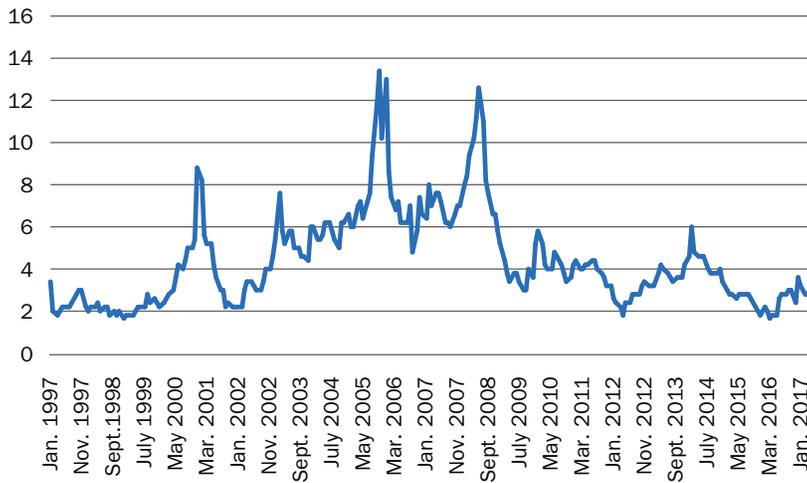
55 Further details on the LCOE estimates, including financing and capital cost inputs, are provided in the Appendix.

56 Slide 12 of the following presentation estimates that LCOE could be reduced by 10% for nth-of-a-kind plants: http://newsroom.nuscale-power.com/sites/nuscalepower.newshq.businesswire.com/files/press_release/additional/Jay_Surina_-_NuScale_Financial_Breakout_Session_0.pdf

57 See, for example, the advanced nuclear energy solicitation issued by the Department of Energy in 2014: <https://energy.gov/articles/department-energy-issues-final-125-billion-advanced-nuclear-energy-loan-guarantee>

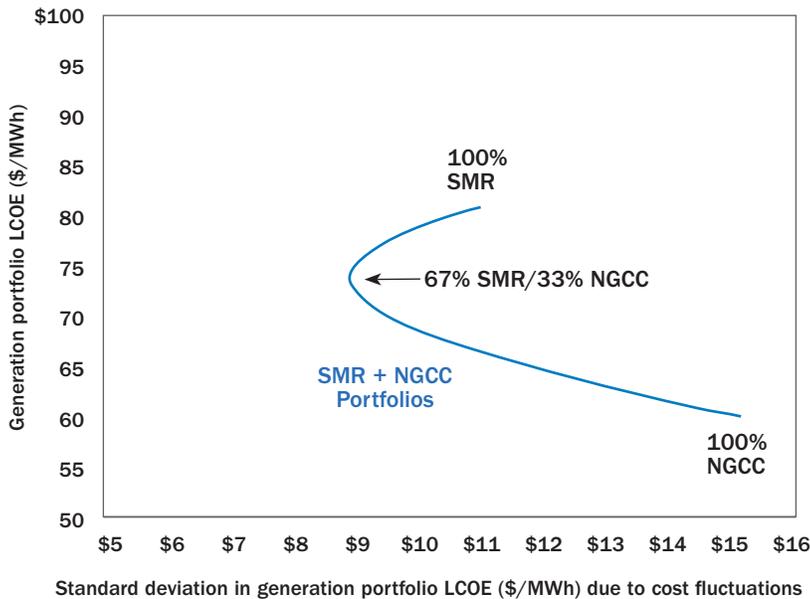
58 Nuclear Energy Institute, "Nuclear by the Numbers," February 2017. See "U.S. Nuclear Plant Costs" table on page 11.

FIGURE 15
Henry Hub Natural Gas Prices in the United States (\$/mmBtu)



Source: EIA; data accessed 6-4-17 at <https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm>

FIGURE 16
Electricity Generating Portfolios with SMRs and NGCC Plants



Utilities would prefer their generation portfolios to be in the bottom left of this type of graph: a lower cost of electricity and a smaller uncertainty associated with that cost. The addition of SMRs to an all-natural gas portfolio raises the portfolio's LCOE, but also helps to reduce the cost volatility associated with natural gas prices. The uncertainty in a portfolio's generation costs is minimized with a combination of SMR and NGCC plants, as the costs drivers for each are largely uncorrelated.

Source: Derived from Figure 4.2.1 of Rothwell and Ganda, "Electricity Generating Portfolios with Small Modular Reactors," May 2014.

gas prices have seen significant volatility in previous decades.

For public power entities and IOUs in rate-regulated states, spikes in natural gas prices can cause significant electricity cost increases if their portfolios are heavily dependent on natural gas plants. Nuclear fuel costs are a smaller percentage of total electricity generating costs, by comparison.⁵⁹ The stability in nuclear generation costs is a secondary reason why utilities would consider adding SMRs to their generation portfolios, even if the LCOE is somewhat above a NGCC plant: they are looking to add fuel diversity and mitigate their vulnerability to natural gas price swings.

As Figure 16 illustrates, decisions on building new generation assets take place in the context of a utility's existing portfolio. If the sole aim of building new generation assets is to produce the lowest LCOE, a utility would build nothing but new natural gas plants; however, this would gradually increase the utility's exposure to natural gas price swings, and increase the vulnerability linked to natural gas supply disruptions from extreme weather events, as discussed in Chapter II. Adding SMRs to a utility's generation assets help to reduce the risk of electricity cost fluctuations for its overall generation portfolio, by mitigating in particular the impacts of natural gas price volatility. As a utility's risk aversion increases, the role of SMRs in generation portfolios becomes more valuable.

The U.S. public power sector (22% of U.S. electricity generation) holds the most promise for SMR deployment, given the different financing structures used. The deregulated market structures in some states are not conducive to building nuclear plants in general, including SMRs. Public power entities, which take a longer view on the value of electricity generation assets and which provide electricity on an at-cost basis to their customers, see the smallest economic gap between SMRs and natural gas plants in terms of LCOE. SMRs would also help owners of electricity generation assets to mitigate their exposure to natural gas price swings.

The next chapter will focus on the largest markets for SMRs, which are located outside the United States. In addition, it will include an estimate for the potential U.S. SMR market based on projected coal and nuclear plant retirements.

59 See Rothwell and Ganda, "Electricity Generating Portfolios with Small Modular Reactors," May 2014.

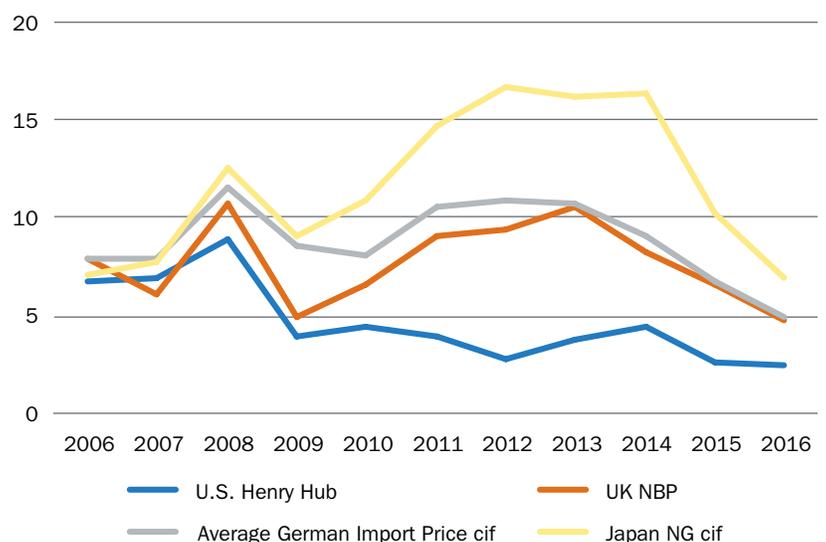
CHAPTER IV

GLOBAL SMR MARKET STUDIES

WHILE NATURAL GAS PRICES are currently low in the United States and thus constitute a formidable challenge to domestic SMR deployment, the situation in other countries is not necessarily the same. As Figure 17 shows, in some countries natural gas prices have been significantly higher. Moreover, for countries with electricity markets governed by state-owned entities, their view of the value proposition for nuclear versus natural gas will be closer to that of the public power entities in the United States, as opposed to merchant companies in deregulated states. Combined with the greater expected electricity demand growth in non-OECD countries versus OECD countries, this is part of the reason why the biggest market for nuclear energy—and SMRs—is outside the United States.

The Department of Commerce estimates the global market for nuclear products, services, and fuel at up to \$740 billion over the next 10 years. According to the U.S. Department of Commerce, every \$1 billion of exports by U.S. companies has represented approximately 5,000 to 10,000 jobs in the United States.⁶⁰ As a result, rebuilding the dominant position the United States once held as the leading exporter of nuclear power plants could create hundreds of thousands of American jobs. The International Trade Administration, part of the U.S. Department of Commerce, issued a report in 2011 that analyzed the prospect markets for SMRs, and examined 27 countries in particular.⁶¹

FIGURE 17
Natural Gas Prices in the United States, the UK, Japan, and Germany



Source: Page 33 of *BP Statistical Review of World Energy*, June 2017.

A. Potential SMR Share of International Nuclear Energy Capacity

One simple approach to estimating the potential international market for SMRs is to assume that SMRs will comprise a small percentage—for example, 10%—of projected new nuclear plant builds, including the replacement of retiring nuclear generation. Projections for global nuclear energy deployment from the IEA and the EIA are used below to estimate potential SMR markets.

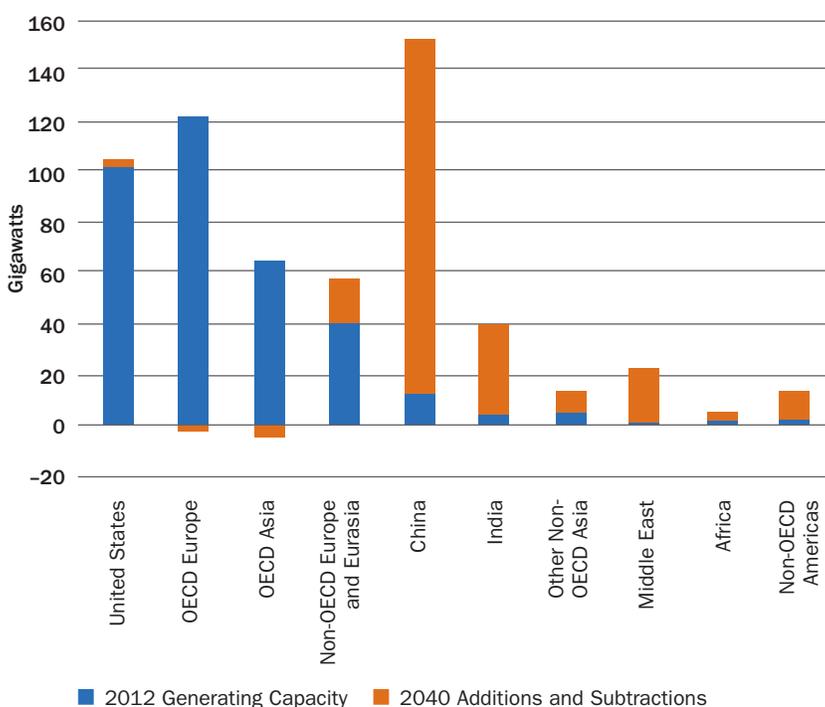
⁶⁰ See Table A-2 of U.S. Department of Commerce, “Jobs Supported by Exports 2016: An Update,” August 2, 2017.

⁶¹ U.S. Department of Commerce International Trade Administration, “The Commercial Outlook for U.S. Small Modular Nuclear Reactors,” February 2011. The appendix to that report discusses the potential best prospect markets for SMRs.

First, the IEA looked at a scenario limiting global warming from greenhouse gas emissions to two degrees Celsius; in this scenario, IEA estimated, global nuclear energy capacity would have to rise to 930 GW in 2050.⁶² Worldwide generation capacity for nuclear energy in 2017 is 391 GW.⁶³ A crude estimate for the potential SMR market might assume that 10% of the new 539 GW of nuclear capacity comes from SMRs. Half of the existing 391 GW may retire by 2050, and if so, that generation will need to be replaced by new nuclear plants in order to reach the projected final capacity. If 10% of those retirements are replaced with SMRs, that would imply a total of 73 GW of SMR deployment by 2050.

A different scenario, still accounting for impacts from the Paris agreement,⁶⁴ comes from the EIA's International Energy Outlook 2016, which assesses that nuclear energy will be the second fastest growing energy source (behind renewables), with an expected growth of 2.3%/yr out to 2040. Electricity generation from nuclear energy is projected to grow to 602 GW by 2040. Virtually all of this growth takes place in non-OECD countries, as shown in Figure 18. As this projection covers a shorter time frame than above, perhaps only 33% of existing plants will retire by 2040. Under the same reasoning described above, SMR deployment may reach 34 GW (though for 2040, instead of 2050). Neither of these estimates include the potential for SMRs to participate in process heat markets.

FIGURE 18
World Nuclear Generation Capacity by Region with Projections for 2040



Gigawatts of nuclear generating capacity in 2012 (blue) and projected additions and subtractions by 2040 (orange).

Source: EIA, "International Energy Outlook 2016," May 2016. Table H5.

B. Potential SMR Additions to U.S. Generating Capacity

In its modeling of the U.S. electrical grid, the EIA does not include an option to build SMRs. The only nuclear energy build the EIA allows for is a large light-water reactor option based on the Westinghouse AP1000. Thus, the EIA projection for SMR deployment in the United States over the next several decades is zero. Separately, absent any additional policies to support continued operation, EIA's assumptions about early retirements of existing nuclear plants are likely too optimistic; there will probably be more retirements. EIA's modeling of the electrical grid also excludes the regulated and public power markets in the United States, where SMRs have a greater economic appeal, as discussed in Chapter III.

EIA's Annual Energy Outlook for 2017 projects that nuclear capacity will decline in the United States from 99 GW in 2016 to 88 GW in 2040. Underlying this projection is an assumption that 25% of U.S. nuclear power plants will retire when they reach 60 years of operation. This is a change from the former EIA assumption that all U.S. nuclear plants would operate for longer than 60 years. The actual number of plants that do not extend their operations to 80 years, however, is likely higher—perhaps close to 50%. Figure 19

62 OECD/IEA and OECD/NEA, "Technology Roadmap: Nuclear Energy," 2015 Edition from IEA Publishing.

63 Data from: <https://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics/World-Nuclear-Generation-and-Capacity>; accessed August 17, 2017.

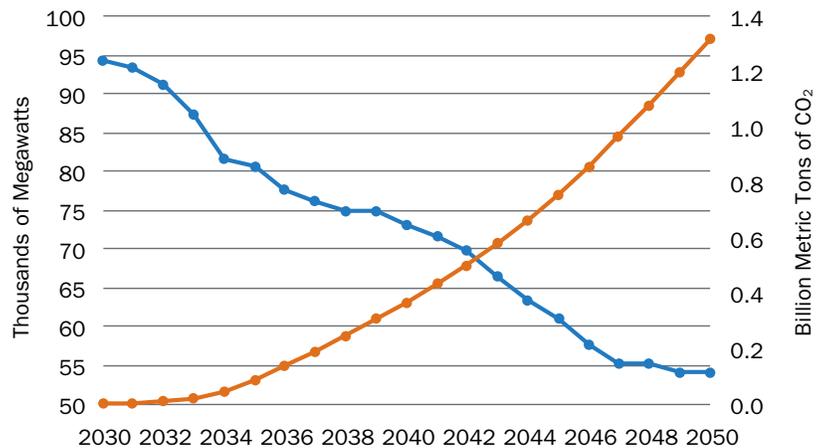
64 International Energy Outlook 2016: "The IEO2016 Reference case also reflects the impacts of broader policies to constrain energy-related carbon dioxide (CO₂) emissions in emerging market countries, such as China and India. In those countries, policymakers have proposed a range of programs that place particular emphasis on the countries' Intended Nationally Determined Contributions for addressing CO₂ emissions reductions as part of the 21st Conference of Parties meetings held in Paris from November 30 to December 11, 2015."

shows total U.S. nuclear generating capacity from 2030 to 2050 assuming a 50% retirement rate during that time period when plants reach 60 years of operation. Also shown are the corresponding cumulative carbon dioxide emissions if those nuclear plants are replaced with NGCC plants. This scenario would lead to an additional 1.3 billion metric tons of carbon dioxide emissions.

EIA's National Energy Modeling System (NEMS) software models the entire United States as being composed of competitive markets.⁶⁵ For the reasons discussed in Chapter III, economic conditions in the competitive markets maximally disadvantage nuclear energy compared to natural gas and renewables. EIA's analysis thus excludes regions in the United States where nuclear energy is a more attractive investment: for example, public power entities (municipalities, political subdivisions, rural electric cooperatives, the Tennessee Valley Authority) do not exist in NEMS for the purposes of estimating new generation capacity.

An alternate way to use EIA modeling to estimate the potential SMR market in the United States is to look at EIA's projections for baseload retirements. A rough estimate assumes (1) that the nuclear and coal retirements in deregulated states will not be replaced with new nuclear, and (2) that SMRs will replace 10% of coal and nuclear retirements in regulated markets. Current nuclear plants are almost equally split between deregulated markets and regulated markets⁶⁶ and roughly 70% of the electricity from U.S. coal plants is generated in regulated states. EIA projects 94 GW of coal capacity will retire between 2016 and 2040 (though that number would be higher if future climate policies are enacted). If 70% of that coal generating capacity is in regulated states, that could mean potentially 6.6 GW of SMR deployment. If half of the nuclear plants in regulated states retire, that could mean another 2.5 GW of SMR power, for a total of 9.1 GW. Extrapolating from a recent estimate⁶⁷ for an SMR project in Idaho, building 9.1 GW of new SMRs could create or sustain 207,000 U.S. jobs.

FIGURE 19
Potential Decline in U.S. Nuclear Generation and Carbon Emissions impact



Decline in U.S. nuclear energy generation capacity (blue) if 50% of U.S. nuclear plants retire after 60 years of operation. Also shown are the cumulative carbon dioxide emissions (orange) if those nuclear reactors are replaced with NGCC plants.

Source: <https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Plant-License-Information>

C. The UK International Market Study

The methods for estimating SMR deployment potential described above are admittedly unrefined. There is no fundamental reason why SMRs would be deployed in the same ratio compared with large reactors across every country and regardless of their purpose.

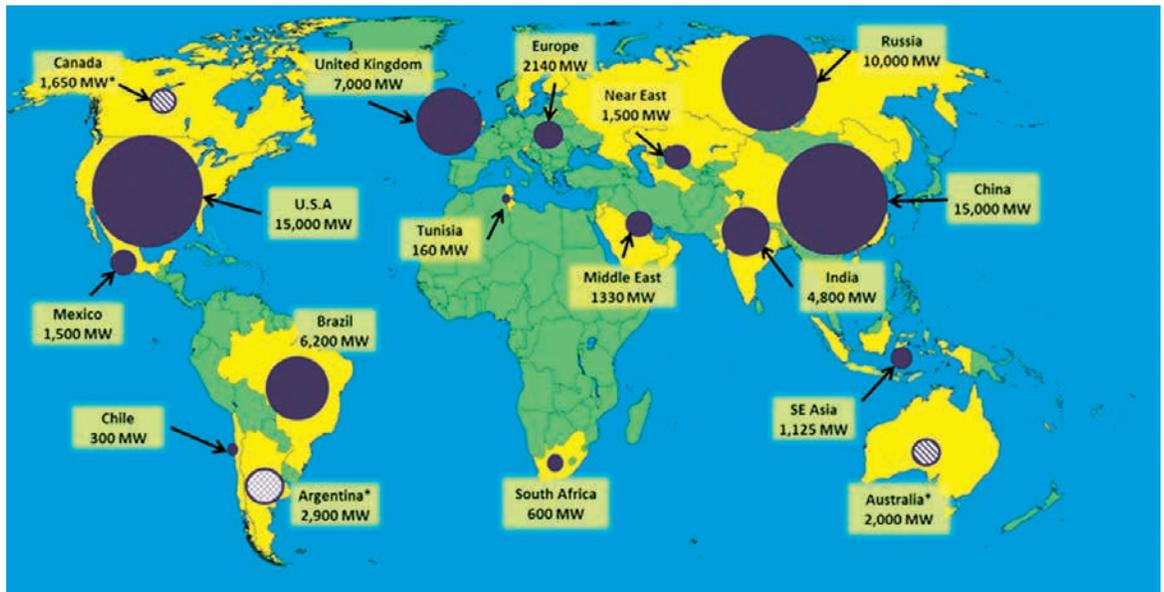
The UK's National Nuclear Laboratory (NNL) published a more in-depth study on SMRs in 2014. The study looked at individual countries in greater detail and examined where and why SMRs might be deployed. The report assumed that large and small nuclear power retained a 12.5% share of global primary electricity production through to 2035. It concluded that the global market for SMRs in 2035 was around 65-85 GW if SMRs can be competitive with large nuclear reactors, which was supported by the study's financial analysis. It further concluded that the global SMR market was likely

65 NEMS documentation can be found at: <https://www.eia.gov/outlooks/aeo/nems/documentation>; the most current version of the Electricity Market Module (2014) states: "The ECP assumes that building power plants will take place in a competitive environment rather than in a rate base or regulated environment" and continues: "This assumption leads to a higher discount rate than a rate base environment in general."

66 Nuclear data from: <https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/Nuclear-Plants-in-Regulated-Deregulated-States>; Coal generation data from: EIA-923 survey form, December 2016.

67 <http://www.world-nuclear-news.org/NN-Local-benefits-from-Idaho-SMR-1508168.html>

FIGURE 20
UK SMR Global Market Assessment



Source: NNL, "Small Modular Reactors Feasibility Study," December 2014.

to be dominated by three suppliers: the United States, China, and Russia.

Figure 20 shows the UK estimates for SMR markets on a country-by-country basis. Excluding Russia, which would not build U.S. SMRs over domestic designs, the potential market for U.S. SMR companies is still 55-75 GW. The numbers shown in Figure 20 exclude markets for desalination and process heat applications, which would also make the potential market larger. The NNL report estimated that the SMR-driven desalination market alone could approach £100 billion (or around \$128 billion).

D. Competition from Non-U.S. SMR Designs

Russia, China, and South Korea all have SMRs in development to potentially take advantage of these business opportunities. Figure 21 shows global SMR technology development by country and several designs are highlighted below.

The HTR-PM is a Chinese HTGR design, where the initial plant comprises two HTR-PM reactor modules powering a single 210 MWe steam

turbine. Construction began on two demonstration units in December 2012, which are slated to begin operation in 2017.⁶⁸ China has signed agreements with Saudi Arabia, South Africa, and the United Arab Emirates to consider the construction of HTGR plants.

The ACP100 is a Chinese 100 MWe integral pressurized water reactor. Between two and six modules can be integrated into a single plant. China National Nuclear Corporation announced in 2016 that a demonstration floating nuclear power plant based on the ACP100 will be built in 2019.⁶⁹ China National Nuclear Corporation has conducted discussions with various countries over the potential use of the technology.⁷⁰

KLT-40S, Russia is continuing with construction of what it describes as the world's first floating nuclear power plant, the Akademik Lomonosov, powered by two 35 MWe KLT-40S reactors. Rosenergoatom expects to begin installation of the plant in September 2019.

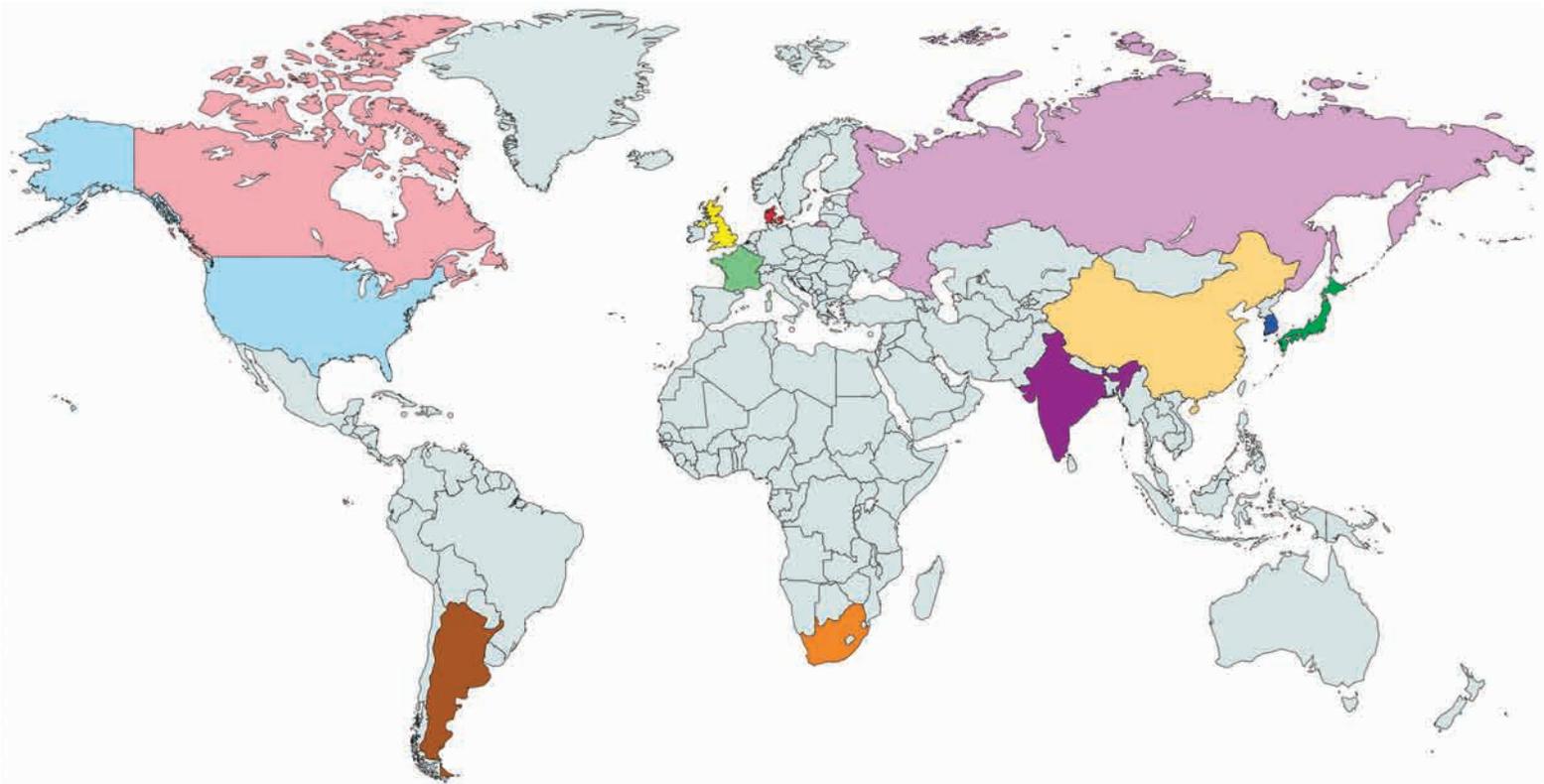
BREST is a 300 MWe lead-cooled fast reactor being developed by Russia, which has approved the

68 <http://www.world-nuclear-news.org/NN-Fuel-loading-starts-at-Chinese-demonstration-HTGR-0704175.html>

69 <http://www.neimagazine.com/news/newschinas-acp100-passes-iaea-safety-review-4883437>

70 http://www.chinadaily.com.cn/business/2017-04/28/content_29122633.htm

FIGURE 21
Global SMR Technology Development by Country



<p>Argentina</p> <p>CAREM</p>	<p>Denmark</p> <p>MSTW</p>	<p>Japan</p> <p>DMS IMR GTHTR300 4S FUJI</p>	<p>Russia</p> <p>KLT-40S UNITHERM KARAT-45/100 ELENA RUTA-70 RITM-200 VBER-300 ABV-6E SHELF GT-MHR MHR-T MHR-100 BREST-OD-300 SVBR-100</p>	<p>UK</p> <p>Stable Salt Reactor U-Battery</p>
<p>Canada</p> <p>LEADIR-PS IMSR</p>	<p>France</p> <p>Flexblue</p>	<p>Multiple</p> <p>IRIS ThorCon</p>	<p>South Africa</p> <p>PBMR-400 HTMR-100</p>	<p>USA</p> <p>NuScale mPower W-SMR SMR-160 Xe-100 SC-HTGR G4M EM2 SmAHTR LFTR Mk1 PB-FHR ARC-100 Oklo</p>
<p>China</p> <p>HTR-PM ACP100 CAP150/200 ACPR50S</p>	<p>India</p> <p>AHWR-300</p>	<p>South Korea</p> <p>SMART</p>		

Source: Derived from a 2016 presentation by Dr. Hadid Subki from the IAEA Nuclear Power Technology Development Section. The country/SMR list is on slide 6 ("Member States with SMRs") and ARC-100, IRIS, ThorCon, U-Battery, and Oklo have been added. The presentation is available at: https://www.iaea.org/INPRO/13th_Dialogue_Forum/007_Advances_in_Small_Modular_Reactor_Technology_developments.pdf



© China Huaneng Group

An HTR-PM reactor pressure vessel is lowered into the reactor building.

start of construction of the first BREST reactor by 2025, along with a facility to produce the uranium-plutonium nitride fuel.

SMART. South Korea is developing a 100 MWe integral pressurized water reactor. In September 2015, Saudi Arabia's King Abdullah City for Atomic and Renewable Energy and the Korea Atomic Energy Research Institute signed a contract to support cooperation in developing SMART.⁷¹

The potential SMR market in non-OECD countries is likely substantial given the growing demand for electricity in those regions of the world. In OECD countries, such as the United States, the SMR market may be aimed more at replacing retiring coal and nuclear generation. This has been one of the main rationales for SMR development in the United States: that SMRs are better-sized to make use of existing coal plant infrastructure. Separately, if retiring nuclear generation is replaced with

natural gas plants, greenhouse gas emissions will rise substantially and impede emission reduction efforts.

The United States announced that it would withdraw from the Paris agreement on June 1, 2017. The projections used in this Chapter for worldwide growth in nuclear energy depend in part on valuing the low-carbon nature of nuclear energy. To date, no other country has withdrawn from the Paris agreement, so the export opportunities for U.S. companies appear to be intact. Many countries are pursuing SMR designs and successful achievement of domestic SMR deployment (if and when it happens) would be used by those countries as an added marketing pitch to global customers. For that reason, delaying U.S. SMR development would likely lead to a reduced share of the potential global SMR market.

71 <http://www.world-nuclear-news.org/NP-Jordan-and-Saudi-Arabia-team-up-on-uranium-SMRs-2903174.html>

CHAPTER V

THE NATIONAL SECURITY CASE FOR SUPPORTING NUCLEAR ENERGY

THE INTERNATIONAL EXPANSION of nuclear power described in Chapter IV raises an important question: what impact will nuclear energy growth have on the global nonproliferation regime? It also raises a more specific national security question: is the United States comfortable with a diminished role in this evolving 21st century arena? The expansion of nuclear energy will take place with or without U.S. involvement and will further spread nuclear materials, equipment, technology, and expertise into countries where they either do not currently exist or where nuclear power programs are still in early stage development.

The Nuclear Suppliers Group (NSG) sets out conditions that must be met by a recipient country before nuclear equipment, including reactors, can be supplied. The objective of the NSG “is to ensure that nuclear trade for peaceful purposes does not contribute to the proliferation of nuclear weapons or other nuclear explosive devices...”⁷² All of the major suppliers of nuclear reactor technology—including the United States—are members of the NSG; thus, countries that meet the NSG Guideline requirements have multiple supplier options available to them.

As the rest of this chapter will argue, it is in the U.S. national interest to have a substantial portion of new reactor deployments come from U.S. sources, which include conditions that support U.S. non-proliferation, safety, and security stances.⁷³ The U.S.

government benefits in unique ways from a strong domestic nuclear export industry when compared with the benefits of other energy export industries.

A. Atoms for Peace and Early U.S. Leadership

In the 1950s and 1960s, the United States put enormous diplomatic emphasis on guiding the international development of nuclear energy. For instance, the United States led the creation of the International Atomic Energy Agency (IAEA) and the negotiation of the Treaty on the Non-proliferation of Nuclear Weapons (NPT). At the same time, the United States put significant domestic resources into the development and deployment of nuclear energy. When President Eisenhower gave his famous “Atoms for Peace” speech to the United Nations in 1953 and proposed the creation of an international atomic energy agency, he was quick to add:

The more important responsibility of this atomic energy agency would be to devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind. Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power-starved areas of the world.

⁷² See the NSG website for more details: <http://www.nuclearsuppliersgroup.org/en/guidelines>

⁷³ Much of the overall argument in this chapter is also laid out in the 2013 Center for Strategic and International Studies report, “Restoring U.S. Leadership in Nuclear Energy: A National Security Imperative.” That report had a broader focus than just SMRs, but many of the same lines of reasoning apply. The Belfer Center for Science and International Affairs at the Harvard Kennedy School released a report in 2016, “American Nuclear Diplomacy: Forging a New Consensus to Fight Climate Change and Weapons Proliferation,” that lays out additional national security arguments for U.S. engagement in the global nuclear energy enterprise. See also, D. Poneman, “The case for American nuclear leadership,” in the *Bulletin of Atomic Scientists*, 2017, Vol. 73, No.1, 44–47.

Eisenhower went on to stress in that speech that the United States would “be proud to take up with others... the development of plans whereby such peaceful use of atomic energy would be expedited.” His Administration knew that proposing only restrictions on the rest of the world would ultimately be ineffective: there had to be something offered in return.

To help set in motion the creation of a commercial reactor fleet, the Atomic Energy Commission (AEC) cost-shared the development and deployment of commercial reactor projects with private industry in the 1950s and 1960s. The Power Demonstration Reactor Program was launched in January of 1955 and solicited proposals from private industry for the development and implementation of nuclear power reactor concepts. Various types of government assistance were offered, including cost-sharing, waiving AEC charges for fuel use, performance of R&D at AEC laboratories with no charge to participants, AEC financing of all or part of the power reactor construction, as well as others.⁷⁴

These initial public-private partnerships helped the United States begin building a fleet of nuclear reactors, and live up to its commitments under the NPT to help non-nuclear weapon states with peaceful nuclear energy development.⁷⁵ Article IV.2 of the NPT reads:

All the Parties to the Treaty undertake to facilitate... the fullest possible exchange of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy. Parties to the Treaty in a position to do so shall also co-operate in contributing alone or together with other States or international organizations to the further development of the applications of nuclear energy for peaceful purposes, especially in the territories of non-nuclear-weapon States Party to the Treaty, with due consideration for the needs of the developing areas of the world.

This early investment in reactor development was one piece of the offering to the rest of the world as

part of the NPT bargain: if non-nuclear weapon states agreed to not develop nuclear weapons and to accept international inspections of their nuclear facilities, the nuclear weapon states agreed to disarm and also to help the non-nuclear weapon states with peaceful nuclear energy development.⁷⁶

As a result of these early investments, the United States played a leadership role in shaping the emerging global nuclear architecture in the 1950s, 1960s, and 1970s, as shown in Figure 22. When the United States stopped ordering new reactors in the 1980s—while other countries continued designing and building them—it began to lose its leadership position.

As Figure 22 shows, the United States is far from the dominant supplier of reactors that it once was. Since the 1980s, other countries have improved at building and selling reactors. Countries such as Russia and South Korea never stopped nuclear power plant construction and Russia in particular has been the leading supplier of new reactor technology to other countries.

The nations that are dominating the supply of reactors, in addition to Russia, may take approaches to guiding the nonproliferation regime over the next several decades contrary to what the United States would like to see. Unfortunately, the ability of U.S. companies to export nuclear reactors is hampered by a domestic weakness in building new reactors. U.S. nuclear cooperation agreements and private company contracts, taken together, make a comparatively weaker offer next to enticements from integrated, state-owned enterprises.

Russia, for example, has made turnkey offers to other states, along with fuel take-back services.⁷⁷ Private U.S. companies cannot offer fuel take-back themselves, nor can they point to recent domestic nuclear reactor builds in their marketing pitches, as Russia can.

State-owned enterprises have different motivations than private companies, and take a longer and broader view of the advantages of supplying nuclear reactors to other countries. The export of a nuclear reactor is the beginning of a near century-long

74 See pages 3-3 through 3-9 of the “Historical Assessment of Government-Industry Roles in the Nuclear Power Commercialization” chapter of the EPRI white paper at: <https://www.epri.com/#/pages/product/3002008046>

75 Similarly, developed nations pledged to assist developing nations with low-carbon technologies in the Paris Agreement. Article 10, for example, discusses enabling innovation and technology transfer to developing countries.

76 See “Atoms for Peace: A Future After 50 Years?” edited by J. Pilat for a broad review of Eisenhower’s Atoms for Peace program.

77 For example, in Vietnam: “...reactors are to be built over 2017-23 as a turnkey project. Russia’s Ministry of Finance is prepared to finance at least 85% of this first plant, to supply the nuclear fuel and take back the used fuel for the life of the plant.” WNN article: <http://www.world-nuclear-news.org/NN-Russia-signs-framework-agreement-for-Vietnam-Ninh-Thuan-1-03081501.html>

relationship between two countries that intertwines their energy and economic interests to a degree, including education, training, safety, regulation, physical security, cybersecurity, and other areas. While state-owned enterprises are making these geostrategic decisions for their respective countries, there is no formal strategic coordination between private U.S. companies and the U.S. government in this regard.

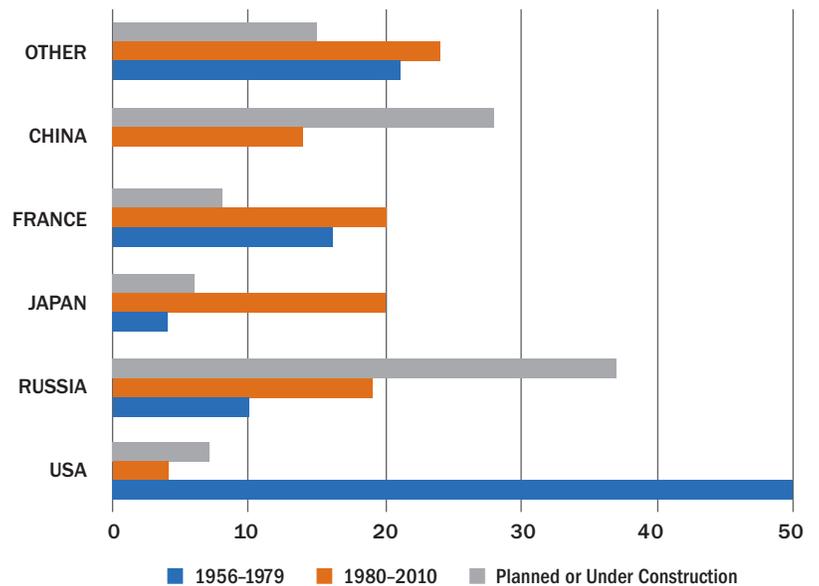
B. Nonproliferation Points of Influence from U.S.-Supplied Reactors

When the United States was supplying reactors in the 1950s through 1970s, the conditions of supply outlined in U.S. nuclear cooperation agreements set out nonproliferation restrictions that supported U.S. policies. Those initial agreements began to set “norms” for how countries should cooperate on civil nuclear power. U.S. supplier policies would continue to evolve over time in reaction to developments such as the NPT entering into force, nuclear explosive tests in India, and the formation of multi-lateral nuclear export control groups, such as Zangger and the Nuclear Suppliers Group. It was partly due to United States dominance of nuclear commerce, however, that the United States had an outsized role in setting those international supplier norms.

Bilateral agreements between the United States and other countries are public documents and detail U.S. supply conditions. The details of nuclear cooperation agreements negotiated by other major suppliers, however, are not necessarily public. In those cases, it is not known what nonproliferation issues are emphasized or ignored. Unless the President determines an exemption is necessary, U.S. nuclear cooperation agreements with non-nuclear weapon states guarantee that:

- safeguards on transferred nuclear material and equipment continue in perpetuity;
- IAEA comprehensive safeguards are applied in non-nuclear weapon states;
- nothing transferred is used for any nuclear explosive device or for any other military purpose;
- the United States has the right to demand the return of transferred nuclear materials and equipment, as well as any special nuclear

FIGURE 22
Historical, Current, and Future Reactor Builds by Supplier Country



Source: Fahad Siddiqui, “Nuclear Energy: On the Way Up, or Out?” 2017. Figure 3.

material produced through their use, if the cooperating state detonates a nuclear explosive device or terminates or abrogates an IAEA safeguards agreement;

- there is no retransfer of material or classified data without U.S. consent;
- physical security on nuclear material is maintained;
- there is no enrichment or reprocessing by the recipient state of transferred nuclear material or nuclear material produced with materials or facilities transferred pursuant to the agreement without prior approval;
- storage for transferred plutonium and highly enriched uranium is approved in advance by the United States; and
- any material or facility produced or constructed through use of special nuclear technology transferred under the cooperation agreement is subject to all of the above requirements.⁷⁸

These conditions of supply, however, only apply when U.S. reactor designs are built. As a recent DOE-National Nuclear Security Administration (NNSA) report⁷⁹ stated:

78 List taken from Congressional Research Service report, “Nuclear Cooperation with Other Countries: A Primer,” December 27, 2016.

79 DOE-NNSA, “International Safeguards, Security, and Regulatory Aspects of U.S. Light Water Small Modular Reactors,” 2014.

Most significantly, these conditions give the United States the ability to ensure international safeguards and physical security at the facility, to control the fate of nuclear materials produced in the facility, and to apply conditions to the further spread of transferred technology. In contrast, the United States would not have these points of influence if reactors were supplied by other nations. Over time, if foreign-designed reactors are consistently chosen over U.S. designs, this would decrease the ability of the United States to influence global supplier norms.

More specifically, when a U.S. reactor is chosen for another country's nuclear program, it gives the United States consent rights over the used nuclear fuel, which then influences the country's fuel cycle choices. Fuel cycle facilities are the most sensitive part of the nuclear technology chain from a nonproliferation perspective. It has been U.S. policy for decades to discourage the spread of enrichment and reprocessing technologies to countries that do not already possess them.

When a U.S. company supplies uranium or material that has had U.S. enrichment or fuel fabrication services applied to it, it comes with U.S. "flags" on it. As a result, the material cannot be further enriched without U.S. consent. A country would be unlikely to build enrichment facilities if the United States was supplying the uranium and did not intend to provide consent for enrichment. Likewise, used nuclear fuel produced by a U.S.-origin reactor—in this case, an SMR—has U.S. flags on it and cannot be reprocessed to access the plutonium without U.S. consent. It would make little sense for a country to build reprocessing facilities if its reactors have all been supplied by a country that does not intend to give them permission to reprocess the material.

C. Needed: A Recommitment to U.S. Leadership in Nuclear Energy

Today, the United States still benefits from R&D investments and public-private partnerships set up by the Atomic Energy Commission in the early years of Atoms for Peace. Those investments ultimately led to the largest nuclear fleet in the world,

and U.S. expertise in operating and maintaining reactors is well established. American universities and national laboratories represent a vital resource that other countries use and strive to replicate.

Current American weakness in the nuclear arena, however, is associated with the deployment stage of reactor development. Without a recommitment by the U.S. government to lead in nuclear energy, U.S. influence in the global nuclear energy and nonproliferation regime will wane.

The following chapter lays out recommendations to establish U.S. leadership in one area: SMRs. If U.S. SMR designs are commercialized and exported, the United States will have a greater role in how new nuclear energy programs around the world evolve. When Atoms for Peace began, the United States had a strategic interest in guiding the development of the nuclear energy and nonproliferation regime. The same is still true today, and while SMRs are just one piece of an overall U.S. nuclear energy and nonproliferation strategy, they could play a valuable role in keeping the United States relevant and engaged. They could also help overcome some of the workforce and supply chain challenges facing the DOE and the U.S. Department of Navy, as described in Box 1.

In declassified documents from 1953, the National Security Council proposed "giving full recognition to the importance of reactor technology to our national security"⁸⁰ and the same assertion could be made today. Along these lines, a recent study found that:

A strong domestic nuclear enterprise will be necessary, perhaps not sufficient, to protect and advance U.S. national security equities as nuclear fuel cycles develop internationally in regions that historically have had little or no nuclear energy.⁸¹

The cost-share agreements and incentives in the 1950s and 1960s set the stage for U.S. dominance of nuclear markets, which served U.S. strategic interests. Another such investment is needed; after a certain point, other countries will be too far ahead of the United States for the actions described in the following chapter to matter.

80 Hearing of the Joint Committee on Atomic Energy, May 26, 1953. Page 25. Testimony from Gordon Dean, Chairman of the Atomic Energy Commission.

81 Energy Futures Initiative, "The U.S. Nuclear Energy Enterprise: A Key National Security Enabler," August 2017.

BOX 1

Workforce and Supply Chain Impacts on DOE and the U.S. Navy

Nuclear reactors provide energy for propulsion to 73 submarines, 10 aircraft carriers, and four research, development, and training platforms in the U.S. Navy, constituting more than 45% of its major combatants.⁸² DOE's Office of Naval Reactors works to provide for the safe and reliable operation of the U.S. nuclear fleet.

Both the DOE and the U.S. Navy have a need for well-trained nuclear engineers and a high-quality supply chain. Service providers, suppliers, and manufacturers in particular help to keep costs down.⁸³ Yet these strategic assets are threatened by a decline in the U.S. nuclear industry, and the Navy may have to depend more on foreign suppliers if the U.S. industry substantially decays. Economies of scale enable suppliers to more efficiently use people, facilities, and manufacturing equipment to meet varying government and commercial orders. DOD costs, and ultimately costs to the federal taxpayer, could rise in the absence of a civilian nuclear program.

If the U.S. nuclear industry is not bringing new and exciting reactor designs to the forefront of global deployment—and the existing U.S. reactor fleet is visibly declining—fewer young people are going to pursue nuclear engineering at the undergraduate and graduate levels. That in turn will result in a smaller pool of talent to draw on for vital national security interests as the existing workforce ages and retires.

Given the interest of the U.S. Navy in a strong domestic nuclear infrastructure, and with the potential for SMRs to provide secure power to installations, DOD may consider various SMR procurement options.



Ohio class submarine.

Source: http://www.navy.mil/navydata/fact_display.asp?cid=4100&tid=200&ct=4

⁸² DOE, "FY 2017 Congressional Budget Request," Volume 1. Page 9.

⁸³ <https://clearpath.org/jays-take/nuclear-the-ecosystem>

CHAPTER VI

RECOMMENDATIONS

THE UNITED STATES SHOULD make a targeted investment to assist first-mover SMR project licensing by the NRC and domestic deployment. Doing so will increase the marketability of those designs to other countries. Those exports will create American jobs and keep the United States involved in the growth and evolution of the nuclear energy and nonproliferation regime as it expands into primarily non-OECD countries.

Many non-light water SMRs require further development before they will be available for commercial deployment. This in turn is balanced by the potential for some of these designs to achieve cost reductions compared with light water-based designs, and thus compete for a broader section of the U.S. and world markets.

Light-water SMRs are the farthest along in terms of engineering completion, technology readiness, licensing, and utility partnering. Successful deployment of light-water SMRs in the 2020s will help pave the way for non-light water SMR deployment by testing the flexibility of the NRC licensing process and potentially by demonstrating new policy and financing instruments, such as federal power purchase agreements. This progress will likely be offset by the relatively high anticipated cost (around \$5000/kw) of light-water SMRs, which

may limit their deployment potential in the United States, though not necessarily in other countries where most of the SMR market growth is expected to take place.

Many non-light water SMRs require further development before they will be available for commercial deployment. This in turn is balanced by the potential for some of these designs to achieve cost reductions compared with light water-based designs, and thus compete for a broader section of the U.S. and world markets.⁸⁴ Non-light water reactors could also make improvements to the nuclear fuel cycle and provide process heat at much higher temperatures for different market applications.

In constructing a nuclear reactor development strategy and deciding how best to allocate limited resources, Congress and the Administration should take into account two principal sources of uncertainty. The first relates to the accuracy of cost estimates based on the stage of project maturity. Cost estimates for large, first-of-a-kind construction projects such as nuclear reactors are subject to substantial uncertainties, even for relatively mature designs halfway to engineering completion. The accuracy of cost estimates based on project maturity is illustrated in the AACE International example shown in Figure 23. While the illustration is drawn from the process industries (e.g., petrochemical), the overall concept of decreasing uncertainty bands for cost estimates as a function of project maturity also applies to power plant construction. This uncertainty in cost estimates makes the down-selection of reactor technologies based on those estimates a challenge for the U.S. government. Thus, a government program should not seek to down-select any more than necessary, nor should it rely primarily

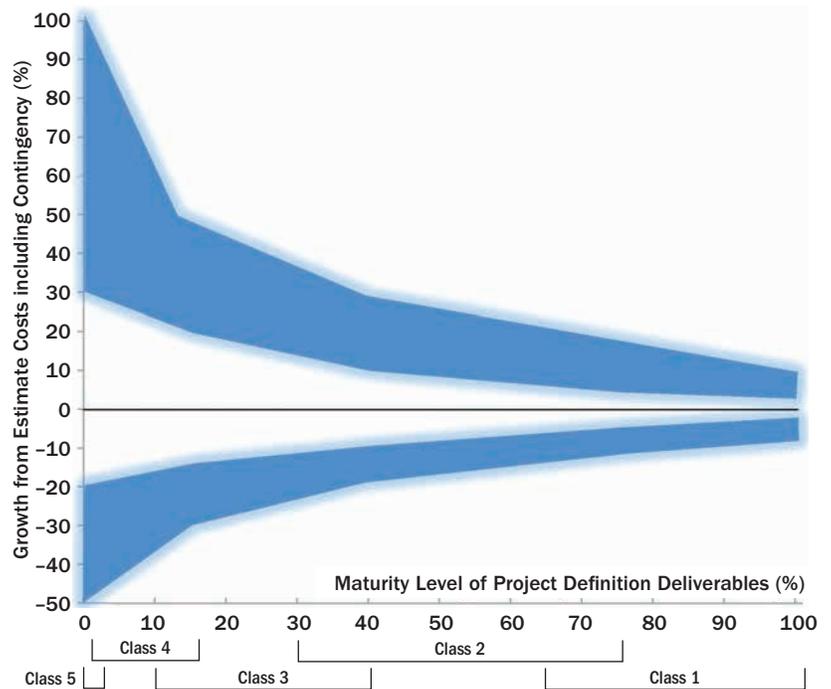
⁸⁴ Energy Innovation Reform Project, “What will advanced nuclear power plants costs?” 2017. See Figure 1 for reactor companies’ self reported capital costs.

on early-stage cost estimates to do so. Instead, it is recommended here that the government use private cost-share commitments as a selection metric that reflects market interest.

A second source of uncertainty relates to the availability of different reactor technologies for commercial deployment. As discussed in other reports,⁸⁵ a key issue for non-light water reactor designs is the need for continued research and/or development to address unique engineering challenges before they are a viable alternative for deployment. Table 2 shows a recent assessment of non-light water reactor technology readiness levels (TRLs).

The TRLs for the non-light water reactors shown in Table 2 are almost all 6 or less, while the equivalent TRLs for some more mature light-water SMR designs would naturally be expected at a higher level—7 or greater—given the larger amount of worldwide and U.S. experience with light-water reactor operation and fuel. While the estimates in Table 2 are representative of the different types of non-light water reactor technologies, specific challenges and opportunities for companies can be found through contact with individual vendors. Different advanced reactors could be available in timeframes ranging from the 2020s to the 2040s,⁸⁶ depending on the amount of development still in process, but also, crucially, on the success of government efforts to accelerate licensing capability,⁸⁷

FIGURE 23
Illustration of the Variability in Cost Estimate Accuracy Ranges



Source: AACE International Recommended Practice 18R-97, Cost Estimate Classification System: As Applied in Engineering, Procurement, and Construction for the Process Industries, reprinted with the permission of AACE International, 1265 Suncrest Towne Centre Dr., Morgantown, WV 26505 USA. © 2016 by AACE International; all rights reserved.

and development and deployment programs such as those described below.

TABLE 2
Estimated Technology Readiness Levels for Various Non-Light Water Reactor Systems

	GFR	LFR	SFR		VHTR	MSR	
	EM2	Gen4	AFR-100	PRISM	SC-HTGR	FHR	LF-MSR
Nuclear Heat Supply	2	3	3	5	5	3	3
Heat Transport	3	3	4	4	5,3	4	3
Power Conversion	3	7	4	7	6	6	6
Balance of Plant	6	6	4	4	6	4	4
Safety	2	3	6	6	6	3	3
Licensing	1	3	3	3	3	2	2
Fuel Cycle	6	6	6	6	NA	NA	5
Safeguards	3	3	3	3	3	3	3
Overall TRL	2	3	3	5	5	3	3

Source: Argonne National Laboratory, Idaho National Laboratory, and Oak Ridge National Laboratory, “Advanced Demonstration and Test Reactor Options Study,” 2017. Tables 2 and B-1.

85 Clean Air Task Force, “Advanced Nuclear Energy: Need, Characteristics, Projected Costs and Opportunities,” (In production).

86 Argonne National Laboratory, Idaho National Laboratory, and Oak Ridge National Laboratory, “Advanced Demonstration and Test Reactor Options Study,” 2017. See page xi of the Executive Summary, Figure ES-2, and the accompanying text. The three DOE national laboratories judge that the less mature reactor technologies may not be available until the 2040s or later.

87 Nuclear Innovation Alliance, “Enabling Nuclear Innovation: Strategies for Advanced Reactor Licensing,” 2016.

Given these two uncertainties, the United States should invest in a portfolio of reactor technologies and provide a continuum of support through the different stages of development using the market to guide technology down-selection, as described below. The government should also provide targeted incentives and support to leverage the specific regions and entities in the United States where nuclear energy is most attractive, as outlined in Chapter III, to achieve deployment of first-of-a-kind light water and non-light water SMRs. Domestic deployment and NRC licensing will provide a marketing advantage to U.S. SMR companies seeking to gain a foothold in the international markets reviewed in Chapter IV. This will ensure the United States has an active role in the development and evolution of the global nuclear energy and nonproliferation regime over the coming decades, supporting U.S. national security interests, as described in Chapter V.

Congress and the Administration should work together to provide a continuum of support for reactor technologies, including design finalization and first-of-a-kind demonstration.

A. U.S. Department of Energy Cost Sharing Programs

Recommendation 1: Congress and the Administration should expand support for new reactor design and licensing to include non-light water designs and extend support through design finalization.

As discussed in Chapter II: The Small Modular Reactor Option, SMRs were originally a class of reactors defined by their size, approach to construction, and multi-modularity. That is, SMRs are independent of the type of the coolant they use, a condition still reflected in U.S. law with the EPACT05 amendments to the Atomic Energy Act of 1954, as amended. Adding support for non-light water designs is thus a logical next step, especially as some non-light water SMRs may soon reach a comparable

stage of development where they need the same type of support that light-water SMRs are receiving now.

The Secretary of Energy Advisory Board (SEAB) Task Force on the Future of Nuclear Power⁸⁸ recommended creating a quasi-public corporation funded by a one-time appropriation of \$5.25 billion in federal funding to match a somewhat larger private sector investment over the course of 25 years. SEAB described a down-select process for reactor technologies across four phases: technology down-select, subsystem development and reactor demonstration preparation, demonstration plant operation, and first-of-a-kind reactor plant operation. While a quasi-public corporation that is not subject to annual budget requests and appropriations would undoubtedly have some operational flexibility and other advantages over a DOE program, this report judges that the creation of such an entity appears unlikely in the near-term, but endorses the funding scale of the SEAB report.

The Breakthrough Institute⁸⁹ has outlined a somewhat different role for the government, based on federal innovation models from other industries, such as commercial spaceflight and wide-body aircraft. The industry group SMR Start⁹⁰ has described a staged approach for DOE, similar in some ways to the SEAB structure, with a decreasing government cost-share role as designs progress through research, development, preliminary engineering and design work, and final engineering and manufacturing development. The percent of cost-share commitment by the private sector at each phase should be used as a selection criterion by DOE to differentiate between proposals by commercial entities seeking federal cost shares. In general, this report endorses an approach that relies more on the market to provide down-selection of reactor technologies. As the percentage of cost share and total amounts of funding from the private sector increase from one stage to the next, the market will in a sense decide what technologies make it to the end, as private sector investors will choose whether or not to provide the requisite funds for each successive stage. Additional research, development, and demonstration recommendations needed to support non-light water reactors will be described in greater detail separately.

88 Final report, Secretary of Energy Advisory Board Task Force on the Future of Nuclear Power, September 22, 2016.

89 Breakthrough Institute, "How to Make Nuclear Innovative," 2017. Page 23: "Public investments to demonstrate and commercialize advanced nuclear design should follow private investment, not lead it, and avoid early down-selection of single favored technologies."

90 SMR Start, "Advanced Nuclear Commercialization Model," June 22, 2017. Page 2: "...rely on the market to provide down selection of technologies."

Design finalization or first-of-a-kind demonstration should be the endpoint for government cost share support for reactor design development, depending on the commercialization pathway for any given technology.⁹¹ The initial SMR LTS program was modeled on the public-private partnerships in the Nuclear Power 2010 (NP2010) program, which included design finalization support. The total funding for NP2010 was \$655 million across 11 years (FY2001 to FY2011),⁹² while the first funding for SMR LTS occurred in FY2012 and the program is currently slated to finish in a shorter amount of time than NP2010 and with a smaller amount of total funding (\$390 million). The SMR LTS cost-share agreements with utility partners for site licenses (\$16.6 million for UAMPS and \$36 million for TVA) are well below the equivalent agreements in NP2010 for site license work (\$118 million for NuStart and \$73 million for Dominion). The total amount of funding for light-water SMR development should at least match the \$655 million from the NP2010 program used to support large light-water reactor designs, though there are valid arguments for why the investment should be greater.⁹³ DOE recognized that SMR development needed more assistance than SMR LTS in its “Energy Innovation Portfolio Plan FY 2018-FY2022” report, which proposed an SMR Enterprise Innovation program funded at the level of \$750 million.⁹⁴

B. Federal Tax Incentives

Recommendation 2: Congress should amend the nuclear energy production tax credit. *Congress should amend section 1306 of EPACT05 to remove the in-service date of January 1, 2021, raise the cap to 9000 MW, allow nonprofit public power entities to qualify, and raise the payment rate for new deployments to 2.7 cents/kWh.*

EPACT05 created a PTC for new nuclear plants to help incentivize new builds and de-risk first mover projects. The existing PTC, however, has an in-service date of January 1, 2021 for new

nuclear builds, a deadline which effectively disqualifies new designs, as no other reactors could be operational in the United States prior to 2021. In addition, the two early mover utilities on SMRs are not-for-profits, and the language in Section 1306 of EPACT05 that refers to “the taxpayer” would disqualify them a second time. The language in the renewable energy PTC enables not-for-profits

The percent of cost-share commitment by the private sector at each phase should be used as a selection criterion by DOE to differentiate between proposals by commercial entities seeking federal cost shares.

to qualify, and the nuclear energy PTC should be amended to provide similar treatment.

DOE’s Quadrennial Energy Review recommended that the in-service date in the EPACT05 production tax credit be extended and that the national megawatt capacity limitation of 6000 MW be raised. This report concurs and recommends that the in-service date be removed. The report recommends that the cap in EPACT05 be raised to 9000 MW to allow for additional capacity beyond the first wave of reactors under construction now. These two changes would incentivize all types of SMRs.

EPACT05 currently specifies a payment rate of 1.8 cents/kWh. But as a static rate (it is not adjusted over time for inflation), it represents a diminishing value to utilities each subsequent year. The renewable energy tax credit, in contrast, was structured to adjust for inflation. The SEAB report recommended that a production tax credit of 2.7 cents/kWh be established for advanced nuclear facility construction, and this report concurs. Language should be added to EPACT05 to raise the payment rate to 2.7 cents/kWh for new reactor deployments.

91 For example, in the case of a light water SMR, a demonstration project may not be needed, while in a more revolutionary design, like a molten salt reactor, it may be necessary to build a demonstration with government cost sharing before a commercial product can be finalized.

92 From email supplied by DOE Office of Nuclear Energy on 3-30-17

93 William J. Madia, Gary Vine & Regis Matzie, “Small Modular Reactors: A Call for Action,” 2015. Excerpt: “For perspective, the four US integral PWR SMR designs had less detailed engineering completed as they competed for DOE LTS funding than was already done on the AP1000 and ESBWR (GE-Hitachi’s Economic Simplified Boiling Water Reactor) at the beginning of the NP 2010. DOE and industry should therefore expect that any program to deploy SMRs would take at least as much time and resources as the NP 2010 program.”

94 DOE, “Energy Innovation Portfolio Plan FY2018-FY2022,” January 2017.

C. Power Purchase Agreements for Federal Facilities

Recommendation 3a: Congress should enable federal facilities to enter into power purchase agreements for low-emission technologies for periods of 20 years or greater.

In the United States, federal power purchase agreements have been used to encourage domestic deployment of clean energy technologies. For example, in 2015, the U.S. Navy announced a 25-year, 150 MW purchase of solar energy from a developer in Arizona for 14 naval installations in California.⁹⁵ The Navy worked with WAPA to gather bids from solar developers, and WAPA managed power scheduling services to bring the power from the solar site in Arizona to the Navy installations in California.

In general, federal agencies are allowed to enter into five-year agreements, though the U.S. General Services Administration has delegated authority to DOE to enter into 10-year agreements. Both of these time periods, however, are too short for utilities to use in obtaining financing for new power plant construction.

WAPA has also worked with DOE sites to enable longer-term power purchase agreements for renewable energy. For example, the National Renewable Energy Laboratory entered into a 20-year power purchase agreement with a solar developer, also utilizing WAPA.⁹⁶ In 2015, DOE-NNSA announced that it had finalized a 20-year power purchase agreement (also utilizing WAPA's authority) with a solar developer onsite at Lawrence Livermore National Laboratory for a 3 MW solar project. The solar developer will sell the renewable power to WAPA through a 20-year purchase contract and DOE-NNSA will purchase the power for Lawrence Livermore National Laboratory

and Lawrence Berkeley National Laboratory.⁹⁷

The projects involving WAPA are somewhat unique within the federal government. WAPA's authorities have allowed it to work with federal facilities to compile purchasing schedules that better match the loan repayment schedules for power generation. In general, federal agencies are allowed to enter into five-year agreements, though the U.S. General Services Administration has delegated authority to DOE to enter into 10-year agreements. Both of these time periods, however, are too short for utilities to use in obtaining financing for new power plant construction. For that reason, the DOE's Quadrennial Energy Review recommended that Congress authorize all federal agencies to negotiate 20-year power purchasing authorities for clean energy.

This study did not identify any evidence that the U.S. government has executed a power purchase agreement for nuclear power in recent decades. The DOE recently contracted a study of power purchase agreement options for federal facilities to take power from SMR projects.⁹⁸ The first phase of the study looked at the broad authorities that federal facilities have, and in particular looked at specific options available for federal facilities to take power from the SMR project in Idaho. The second stage is examining how SMRs could provide energy resiliency to federal facilities and looks at the TVA SMR project. If the U.S. government were able to negotiate a power purchase agreement for nuclear energy, it could potentially establish a new policy instrument that could be used to assist with deployment of non-light water reactor technologies.

Separately, despite the connection to U.S. non-proliferation interests, nowhere in the U.S. national security complex is the importance of a vital nuclear energy industry explicitly valued. One possible way to remedy this is through power purchase agreements from DOD and NNSA facilities.

Recommendation 3b: The Secretary of Energy should work with the WAPA Administrator and DOE, DOD, and other federal facilities in the WAPA territory to procure 100-200 MW of power from the UAMPS SMR project.

⁹⁵ http://www.navy.mil/submit/display.asp?story_id=90684

⁹⁶ DOE presentation on power purchase agreements: https://www1.eere.energy.gov/femp/pdfs/afo_ppa_pres.pdf

⁹⁷ NNSA press release: <https://nnsa.energy.gov/mediaroom/pressreleases/solarpower>

⁹⁸ Kutak Rock and Scully Capital, "Purchasing Power Produced by Small Modular Reactors: Federal Agency Options," January 2017. Available at: <https://www.energy.gov/ne/downloads/purchasing-power-produced-small-modular-reactors-federal-agency-options>

DOE, DOD, and other federal agencies should pursue a power purchase agreement for the SMR project at INL brokered by WAPA. In the Northwest, the presence of cheap hydropower means that DOE and DOD sites pay less in electricity than their counterparts in the Southwest. Aggregating power from federal facilities within WAPA's territory will mean that some facilities may pay less for the electricity from an SMR than they currently pay, while others may pay more. The Secretary of Energy needs to communicate to the relevant lab directors in the West that this negotiation is a priority, and request they purchase between 10% and 25% of their power needs from the SMR project sited at INL—the negotiated rate could be lower if the production tax credit described above is available.

Recommendation 3c: The Secretary of Energy should work with TVA and DOE, DOD, and other federal facilities in the TVA territory to procure 100-200 MW of power from the TVA SMR project.

DOE should pursue a power purchase agreement for the SMR project in Tennessee near Oak Ridge National Laboratory (ORNL). As the early site permit application submitted by TVA indicates, the SMR project could be structured to utilize underground transmission lines to increase security of power supply to ORNL and Y-12. By virtue of their smaller size and multi-modularity, SMRs are capable of providing highly reliable and secure power.⁹⁹ Specific federal facilities may require a certain level of reliability for missions of national security importance. An SMR-powered microgrid could provide enhanced reliability and other advantages for such facilities. SMRs have several inherently robust features and in combination with microgrid technologies and transmission and distribution systems, could be incorporated as part of a system that is less vulnerable to intentional destructive acts or natural phenomena. Power purchase agreements could also recognize the national security benefits of SMR development.

There are two somewhat unique circumstances to the TVA project. First, as TVA is part of the federal government, the power purchase agreement might instead take the form of an inter-agency

agreement. This could help the federal government value qualities like resiliency, emissions reductions, and mission flexibility (e.g., generating data for DOE's modeling and simulation activities, demonstrating process heat applications, etc.). Second, the federal facilities that would be taking power from the SMR project are themselves already TVA customers, and so the inter-agency agreement might look more like a contract for differences between the current rate and the highly reliable power rate.

DOE should commission a study to identify federal facilities, power demands, and potential payment rates to issue a request for proposals from nuclear reactor companies as a means of encouraging the deployment of new reactor technologies.

Recommendation 3d: DOE should identify options for federal power purchase agreements to help enable deployment of new reactor technologies.

For recommendations 3b and 3c, the reactor owners and operators have already been identified, as have the sites of the potential reactors. What remains in 3b and 3c is for DOE to identify federal facilities and specified amounts of power to take from the reactor projects, and also to negotiate payment rates. DOE should commission a study to look at the reverse: identifying federal facilities, power demands, and potential payment rates to issue a request for proposals from nuclear reactor companies as a means of encouraging the deployment of new reactor technologies. Issuing a request for proposals would be an entirely different way of stimulating nuclear energy deployment in the United States, though similar to mechanisms that have been pursued in countries such as the United Kingdom. The study would need to account for the variety of factors that go into power purchase agreements, including: state and federal regulatory environments, the total power demands of individual federal facilities, available federal authorities

⁹⁹ Doyle, J., et al, "Highly Reliable Nuclear Power for Mission-Critical Applications," Proceedings of ICAPP 2016, April 17–20, 2016.

for given regions and facilities, and regional power prices (both electricity and heat).

D. State Clean Energy Standards

Recommendation 4: States should expand any existing or proposed Renewable Portfolio Standards into Clean Energy Standards. *States should expand renewable portfolio standards into clean energy standards to increase the total amount of low-carbon electricity required and give utilities greater flexibility in reducing air pollution and greenhouse gas emissions, while also meeting reliability requirements.*

State renewable portfolio standards have been remarkably successful in helping to create demand for renewable energy. To date, nothing comparable has been established that would encourage new nuclear plant construction. Allowing dispatchable low-emission technologies—conventional, hydro-

State renewable portfolio standards have been remarkably successful in helping to create demand for renewable energy. To date, nothing comparable has been established that would encourage new nuclear plant construction.

electric, nuclear, and fossil plants equipped with carbon capture and sequestration capabilities—to qualify for state clean energy standards would provide utilities with greater flexibility to meet overall societal goals: less air pollution and less greenhouse gas emissions. This could also raise the total amount of electricity covered by state electricity standards. In cases where renewable energy provides a greater value proposition than nuclear energy, clean energy standards would still

be, in effect, renewable energy standards and lead to even more renewable energy deployment. But in the specific sectors where nuclear energy is more attractive to utilities, as described in Chapter III: Where SMRs Are Most Attractive in the United States, state clean energy standards that include nuclear could make it less expensive for utilities to accomplish energy and environmental goals.

As shown in Figure 24, states have been very active in adopting renewable portfolio standards. The requirements vary from state to state, where some requirements apply only to investor-owned utilities, while others may also have requirements for municipalities and rural electric cooperatives. According to Lawrence Berkeley National Laboratory, 20 states and Washington D.C. have percentage-based cost caps in their renewable portfolio standard bills to limit increases in ratepayers' bills.¹⁰⁰

A recent study has shown that expanding state renewable portfolio standards to clean energy standards (or “low carbon portfolio standards”) could be one way forward in decarbonizing the electricity sector by midcentury.¹⁰¹ The study estimated that these clean energy standards could more than double the statutory requirements for clean energy in the United States and prevent more than 320 million tons of carbon dioxide emissions. This would prevent the premature closing of many of America’s nuclear power plants and assure that any future nuclear power plant retirements will create a market draw for low-emission generation, including SMRs. If the existing nuclear fleet retires early and is replaced with natural gas plants, it will erase much of the climate progress brought about by state renewable portfolio standards.

Recently, Massachusetts has proposed exactly such a technology-inclusive approach,¹⁰² while Illinois and New York have extended specific state support for existing nuclear plants, as part of their clean energy strategies.¹⁰³

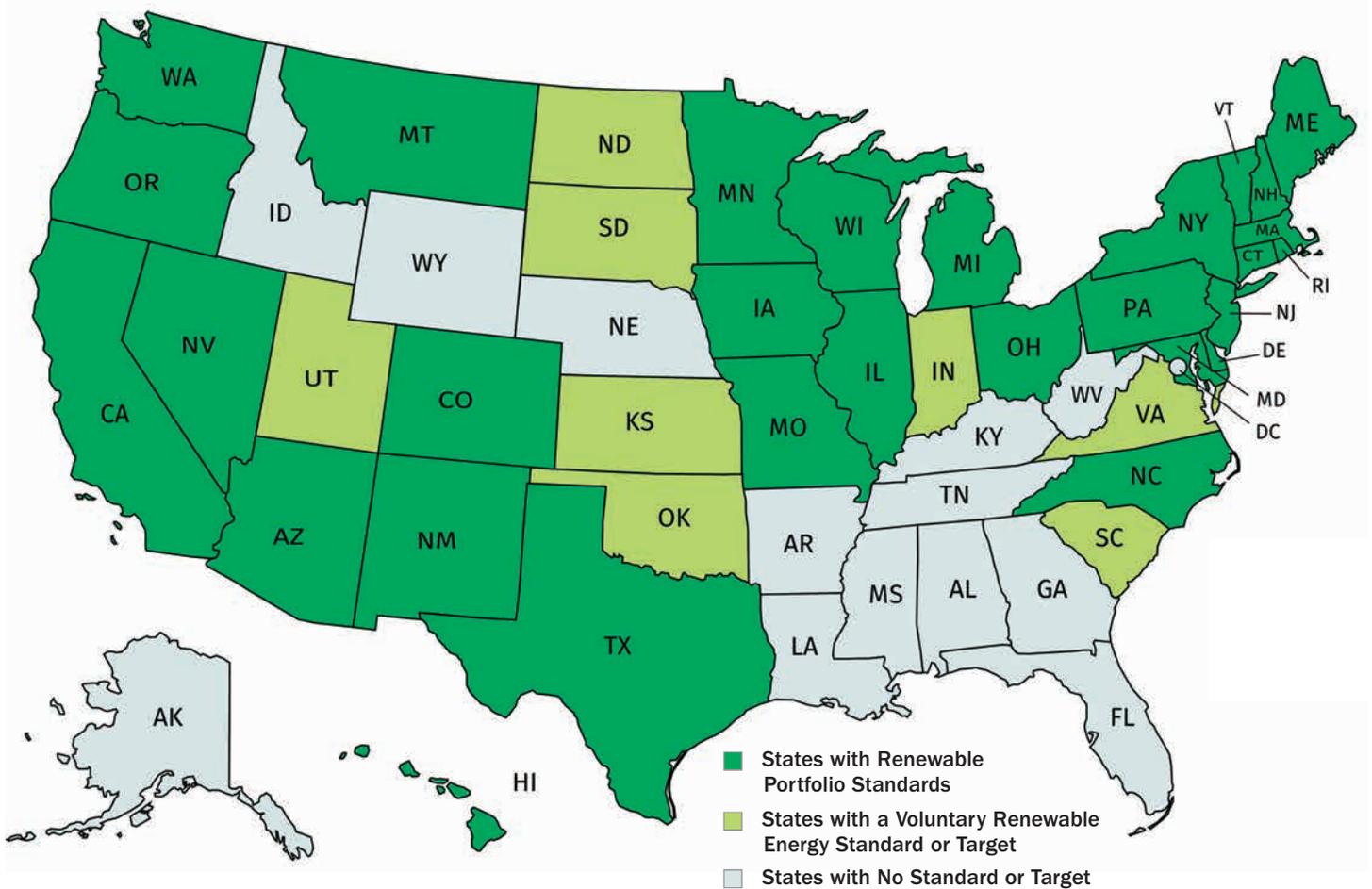
100 National Conference of State Legislatures: <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>

101 Breakthrough Institute, “Low Carbon Portfolio Standards: Raising the Bar for Clean Energy,” 2016.

102 See <http://www.mass.gov/eea/agencies/massdepl/air/regulations/310-cmr-7-00-air-pollution-control-regulation.html>

103 See SB 2814, Public Act 099-0906, 99th Gen. Assemb. (Ill. 2016), <http://www.ilga.gov/legislation/99/SB/PDF/09900SB2814enr.pdf> and <http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7B44C5D5B8-14C3-4F32-8399-F5487D6D8FE8%7D>

FIGURE 24
State Renewable Portfolio Standards and Voluntary Standards or Targets



Source: National Conference of State Legislatures: <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>; accessed on 5-30-17.

These four recommendations would help to create new clean energy options for the United States to accomplish its energy and environmental goals. SMRs offer a different approach to nuclear power plant construction from large reactors and could access new markets, further reducing air pollution and greenhouse gas emissions. The United

States has a national security interest in guiding the development of the global nuclear energy and nonproliferation regime, and developing SMRs is one way for the United States to remain engaged. Successful commercialization and deployment of U.S. SMRs could also create or sustain hundreds of thousands of American jobs.

ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AFUDC	Allowance for funds used during construction
CWIP	Construction work in progress
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPACT05	Energy Policy Act of 2005
EPRI	Electric Power Research Institute
HTGR	High temperature gas reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INL	Idaho National Laboratory
IOU	Investor owned utility
LCOE	Levelized cost of electricity
NEMS	National Energy Modeling System
NGCC	Natural gas combined cycle
NNL	UK National Nuclear Laboratory
NNSA	National Nuclear Security Administration (U.S.)
NP2010	Nuclear Power 2010
NPT	Treaty on the Non-proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission (U.S.)
NSG	Nuclear Suppliers Group
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PTC	Production tax credit
SEAB	Secretary of Energy Advisory Board
SMR	Small modular reactor
SMR LTS	DOE SMR Licensing and Technical Support program
TRL	Technology readiness level
TVA	Tennessee Valley Authority
UAMPS	Utah Associated Municipal Power Systems
WAPA	Western Area Power Administration
WECC	Western Electricity Coordinating Council

APPENDIX

LCOE Calculations

THIS SECTION DESCRIBES THE inputs used to calculate the LCOE estimates provided in Table 1 of Chapter III. These inputs were entered into the Du and Parsons spreadsheet used in their paper, “Update on the Cost of Nuclear Power.”¹⁰⁴ For an investor-owned utility in a regulated state, the return on equity investment allowed is 10%.¹⁰⁵ For a merchant plant in a deregulated state, the return on equity investment expected is 16%, the debt rate for a merchant plant is 7.6%, the debt rate for a regulated IOU is 5.7%, and inflation is assumed to be 2%.¹⁰⁶ The debt comprises 50% of the financing in both cases. The debt rate for a public power entity is 4.5%¹⁰⁷ and the financing in this case is 100% debt with the tax rate set to zero. The construction schedule for an SMR is assumed to be four years where costs are allocated as 25% in year one, 30% in year two, 25% in year three, and 20% in year four. All costs are in 2016\$.

Variable O&M, fixed O&M, and heat rates are taken from Table 8.3 in the January 2017 EIA Electricity Market Module for “Conv Gas/Oil Comb Cycle” (along with NGCC capacity), with 2% escalation from 2015\$ to 2016\$. NuScale overnight cost is reported as \$5078/kw in 2014\$,¹⁰⁸ escalated to \$5283/kw in 2016\$. Owner’s costs

of 20% are applied to both overnight costs above, which make them \$6340/kw and \$1174/kw for SMRs and NGCC plants, respectively. Nuclear decommissioning cost is assumed to be \$350 million (from the 2003 Massachusetts Institute of Technology study) multiplied by the ratio of capital costs (5283/2000) and the ratio of capacity outputs (570/1000) to reach \$527 million. The average price for natural gas in EIA’s Annual Energy Outlook 2017 from 2026–2045 is \$5.06 in 2016\$. Other than the inputs described in this appendix, all other inputs have been left as they were in the 2009 Du and Parsons publication.

TABLE 3
SMR and NGCC Cost Inputs

Parameter	SMR	NGCC
Capacity (MWe)	570	702
Capacity factor	92%	85%
Heat rate (Btu/kWh)	10449	6600
Overnight cost (\$/kw)	5283	978
Incremental capital costs (\$/kw/yr)	0	0
Fixed O&M costs (\$/kw/yr)	100	11
Variable O&M costs (mills/kWh)	2.3	3.5
Fuel costs (\$/mmBtu)	0.67	5

104 The Du and Parsons paper is available at <http://web.mit.edu/jparsons/www/publications/2009-004.pdf> and the associated spreadsheet is available at <http://www.mit.edu/~jparsons/publications/Du%20Parsons%20Update%20Cost%20of%20Nuclear.xls>

105 Page 25 of Edison Electric Institute, Financial Review 2015; average awarded/requested return on equity was 9.85%/10.3%

106 Pages 11–14, https://www.epa.gov/sites/production/files/2015-08/documents/chapter_8_financial_assumptions.pdf

107 This may be somewhat conservative and some public power entities should be able to access debt at lower interest rates. TVA appears to have been able to access debt at around 4% on a consistent basis over the past decade: <http://www.snl.com/IRW/CustomPage/4063363/Index?keyGenPage=1073746881>

108 <http://www.nuscalepower.com/smr-benefits/economical/construction-cost>

Enabling Nuclear Innovation

Leading on SMRs



The purpose of this report is to propose actions for state and federal governments that will facilitate the development and deployment of U.S. small modular reactor (SMR) designs. These power plants could provide the United States and the world with a clean, dispatchable option to improve people's lives, while at the same time reducing greenhouse gas emissions and air pollution.

Recommendations include cost-sharing programs at the U.S. Department of Energy to reduce regulatory risk and accelerate design availability, tax incentives to overcome first-mover barriers to deployment, power purchase agreements for federal facilities to recognize the clean energy and national security benefits of SMR deployment, and state clean energy standards to increase demand for low-carbon technologies, such as SMRs.

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