ELECTRIC POWER RESEARCH INSTITUTE

Program on Technology Innovation: Review of Advanced Reactor Technology with Emphasis on Light-Water and Non-Light-Water Small Modular Reactor Designs

2016 TECHNICAL REPORT

Program on Technology Innovation: Review of Advanced Reactor Technology with Emphasis on Light-Water and Non-Light-Water Small Modular Reactor Designs

All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

YES NO

EPRI Project Managers
A. Sowder
C. Marciulescu

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue
Palo Alto, CA 94304-1338
USA

PO Box 10412
Palo Alto, CA 94303-0813
USA

800.313.3774
650.855.2121

askepri@epri.com

www.epri.com

3002009413
Final Report, November 2016

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Acknowledgments

The Electric Power Research Institute (EPRI) prepared this report.

Principal Investigators
A. Sowder
C. Marciulescu

This report describes research sponsored by EPRI.

Much of this report's content resulted from a joint project to update advanced nuclear generation information in the EPRI Technical Assessment Guide (TAG®) for Power Generation and Storage Technology Options, which is maintained by the Environment Sector Program P178 for Technology Assessment, Market Analysis, and Generation Planning. The collaborative effort was managed by Clarence Lyons and co-funded by EPRI Program 178A. This support is gratefully acknowledged.

This publication is a corporate document that should be cited in the literature in the following manner:

Program on Technology Innovation: Review of Advanced Reactor Technology with Emphasis on Light-Water and Non-Light-Water Small Modular Reactor Designs.
EPRI, Palo Alto, CA: 2016.
3002009413.

Abstract

Public and private sector interest drives the need for up-to-date information on existing and future nuclear technologies, regulatory frameworks, and key economic factors for nuclear power alternatives. The information presented in this report is based on technology improvements, existing risks, and other key factors that influence decisions associated with selecting, planning, and implementing nuclear power technologies. The topics addressed in this report include the following:

- Reactor technology including advanced light-water reactors, light water small modular reactors (lwSMRs), and advanced concepts based primarily on coolants other than water
- Economics and current power generation trends
- Regulatory frameworks, risks, and estimated costs
- Key markets, ongoing projects, and emerging opportunities

Continued operation of light water reactors (LWRs) provides a dispatchable, low carbon foundation on which expanded roles and new missions for nuclear in the form of lwSMRs and advanced reactors can be established. The lwSMRs offer potentially affordable replacement options for smaller retiring fossil plants. Meanwhile, advanced reactors promise substantial improvements over existing nuclear generation in terms of safety, economics, performance, and long-term energy security. Advanced reactors employ a combination of new coolants, fuels, materials, and power conversion technologies that, if commercialized, would offer substantial improvements over existing generation technology in terms of safety, economics, performance, and long-term energy security.

The challenges and opportunities associated with development and deployment of new nuclear generation technologies limit what can be stated conclusively about the future role of nuclear in a specific country or region. Progress in new-build programs for lwSMRs and advanced reactors will depend heavily on successful licensing, construction, and operation of the various demonstrations, first-of-a-kind commercial units, and other early technology adopters.

Keywords

Advanced nuclear technology
Small modular reactors
Non-light-water reactors
Advanced reactors
Light water reactors (LWRs)

ELECTRIC POWER RESEARCH INSTITUTE

Deliverable Number: 3002009413

Product Type: Technical Report

Product Title: Program on Technology Innovation: Review of Advanced Reactor Technology with Emphasis on Light-Water and Non-Light-Water Small Modular Reactor Designs

PRIMARY AUDIENCE: Existing and prospective nuclear reactor technology customers (electric power utilities, owners) and advanced reactor technology developers and vendors

SECONDARY AUDIENCE: General public and industry partners with an interest in understanding the key technologies, economic attributes, regulatory frameworks, economic factors, and markets for existing light-water and non-light-water reactors

KEY RESEARCH QUESTION

Light-water small modular reactors (lwSMRs) and other advanced nuclear generation concepts—based primarily on coolants other than water (helium, molten salts, and liquid metals such as sodium or lead-bismuth)—offer compelling options for meeting future energy needs. They accomplish this by taking advantage of inherent safety options, new fuels and fuel cycles, and advanced energy conversion technologies. While most of the lwSMR and advanced non-light-water-based reactor technologies have already been demonstrated at some scale, there are other barriers and risks that preclude the deployment of these nuclear power reactors. These obstacles exist because of economic issues, existing regulatory frameworks, key market needs, and technology factors. EPRI seeks to answer the fundamental question, "What do current and potential nuclear technology customers need to know about existing and advanced reactor technologies in order to consider the adoption of nuclear technologies as part of a future electricity and energy generation infrastructure?"

RESEARCH OVERVIEW

In light of substantial changes in the nuclear generation landscape with respect to lwSMRs and advanced reactor technologies, this document provides an update of advanced nuclear generation systems, reviewing the current state and trajectory of the technology and focusing on six key areas:

- Reactor technology descriptions
- Economics
- Siting requirements
- Regulatory frameworks, design certification, and licensing
- Key markets
- Ongoing and future developments

KEY FINDINGS

- Advanced reactors and lwSMRs offer attractive energy generation options for the future by taking advantage of new fuels and fuel cycles, inherent safety features, higher operating temperatures, and advanced energy conversion technologies.
- Advanced reactors and lwSMRs are either operating, under construction, or planned in a number of countries throughout the world. While a nuclear "renaissance" has not materialized in the United States and other western countries as expected, a robust global market exists for nuclear reactors.

- Non-electricity applications present important missions for advanced nuclear reactors.
- While there are many technology choices to choose from for lwSMRs and advanced reactors, the deciding factors that will heavily influence their construction and deployment will be specific to the local policies, licensing framework, and market drivers.

WHY THIS MATTERS

As with the commercialization of existing large water-based nuclear reactors, early and meaningful information and engagement of prospective customers, developers, and vendors provides many potential benefits, including:

- Identification of unaddressed gaps and risks
- Enhanced communication to increase the chances for an early buy-in from potential nuclear technology customers
- A common approach to information gathering and communication

HOW TO APPLY RESULTS

This report provides an information platform intended to create a better understanding of the existing challenges and opportunities related to the development, deployment, and application of the existing lwSMR technologies as well as advanced non-light-water-based nuclear reactors.

LEARNING AND ENGAGEMENT OPPORTUNITIES

EPRI has established the Advanced Reactor Strategic Program and Technical Advisory Group (TAG) to interface with stakeholders from industry, government, and academia. Users of this report may be interested in and benefit from participation in related workshops and TAG meetings sponsored by EPRI. For more information, please contact Andrew Sowder at (704) 595-2647 or asowder@epri.com.

EPRI CONTACTS: Andrew Sowder, Principal Technical Leader, (704) 595-2647, asowder@epri.com

PROGRAM: Advanced Nuclear Technology, 41.08.01, 2016

IMPLEMENTATION CATEGORY: Reference

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

Definitions

The following terms, acronyms and initialisms appearing in figures and text are defined as follows:

- AGR: Advanced Gas-cooled Reactor
- BWR: Boiling Water Reactor
- CANDU: Canada Deuterium Uranium reactor
- GCR: Gas-Cooled Reactor
- GFR: Gas-cooled Fast Reactor
- HTGR: High Temperature Gas-cooled Reactor
- LEU: Low Enriched Uranium
- LFR: Lead-cooled Fast Reactor
- lwSMR: light water Small Modular Reactor
- LWR: Light Water Reactor
- Magnox: *Magnesium Non-Oxidizing* (a Generation I gas-cooled reactor deployed in the United Kingdom named for the magnesium-aluminum alloy used for fuel cladding)
- MSR: Molten Salt Reactor
- PHWR: Pressurized Heavy Water Reactor
- RPV: Reactor Pressure Vessel
- RVACS: Reactor Vessel Auxiliary Cooling System
- PWR: Pressurized Water Reactor
- SCWR: Supercritical Water Reactor
- SFR: Sodium-cooled Fast Reactor
- SMR: Small Modular Reactor
- VHTR: Very High Temperature gas-cooled Reactor

Table of Contents

Abstract V

Executive Summary VII

Section 1: Introduction 1-1
1.1 Introduction and Context 1-1
1.2 Background 1-2
1.2.1 Generation I 1-2
1.2.2 Generation II 1-3

Section 2: Nuclear Generation Role 2-1
2.1 Nuclear Generation Current Share of Electricity Mix 2-1
2.2 Future Role for Nuclear Generation 2-1
2.3 Technology Options for New Nuclear Generation ... 2-4
2.3.1 Generation III 2-4
2.3.2 Small Modular Reactors (SMRs) 2-5
2.3.3 Generation IV – Advanced Reactors 2-6
2.4 Challenges and Opportunities for New Nuclear 2-7
2.4.1 Uncertainty 2-7
2.4.2 Investment to Replace Retiring Assets 2-9
2.4.3 Private Sector Interest and International Partnerships for Nuclear Investment 2-10
2.4.4 Access to New Markets via New Products and Applications 2-11
2.4.5 Clean Slate for Emerging Energy Markets..... 2-12

Section 3: Reactor Technology Descriptions 3-1
3.1 Generation III/III+ 3-1
3.2 Small Modular Reactors 3-1
3.3 US Small Modular Reactor Designs 3-5
3.3.1 BWXT mPower 3-5
3.3.2 NuScale Power 3-6
3.3.3 Holtec Inherently-Safe Modular Underground Reactor (HI-SMUR SMR-160) 3-8
3.3.4 Westinghouse Small Modular Reactor (W-SMR) 3-8

3.4 Non-USD Small Modular Reactor Designs 3-9
3.4.1 CNNC ACP100 3-9
3.4.2 CNEA CAREM 3-10
3.4.3 KAERI SMART 3-10
3.4.4 OKBM Afrikantov KLT-40S 3-11
3.4.5 OKBM Afrikantov VBER-300 3-11
3.4.6 SNERDI/SNPTC CAP-200 3-11
3.5 Advanced Reactors 3-12
3.5.1 Small Modular Generation IV Systems.......... 3-12
3.5.2 Other Notable Advanced Reactor Designs ... 3-22
3.6 Key National Gen IV R&D Programs 3-24
3.6.1 China 3-24
3.6.2 France 3-25
3.6.3 India 3-25
3.6.4 Japan 3-26
3.6.5 Russia 3-27
3.6.6 South Korea (Republic of Korea).................. 3-27
3.6.7 United States 3-28

Section 4: Economics of Nuclear Reactors 4-1
4.1 Economics of Large LWR Plants 4-1
4.2 Economics of lwSMRs and Advanced Reactors 4-3
4.3 Estimated Costs for Advanced Reactor Demonstrations and Prototypes 4-6
4.4 Sitting Requirements 4-8
4.5 Land Use Requirements 4-9
4.6 Water Use and Cooling Requirements 4-12
4.7 Regulatory Frameworks, Design Certification and Licensing 4-14
4.8 Generation III+ LWR Design Certification and Licensing 4-15
4.9 lwSMR Design Certification and Licensing............. 4-17
4.10 Generation IV Design Certification and Licensing. 4-18

Section 5: lwSMR and Advanced Reactor Commercial Applications..................... 5-1
5.1 Key Markets for lwSMRs and Advanced Reactors 5-1
5.2 Ongoing and Future Developments 5-4

List of Figures

Figure 1-1 Evolution of Commercial Nuclear Power Reactor Technology by Generation. 1-2

Figure 1-2 Construction Starts for Nuclear Reactors Worldwide. 1-4

Figure 2-1 Snapshots of New Commercial Nuclear Reactors under Construction Worldwide by Country (LEFT) and by Type (RIGHT). 2-3

Figure 2-2 Projected Nuclear Generation Capacity (GWe) and Contribution (%) to Global Total under the Two Degree Temperature Rise Scenario (2DS)...................... 2-3

Figure 2-3 Generation Capacity at Risk in the United States over the Next Three Decades. LEFT – Retirement of U.S. Nuclear Fleet for 60- and 80-Year Lifetimes. RIGHT – Near-Term Retirement of U.S. Coal Fleet for the Evolving Economic and Regulatory Environment. 2-7

Figure 2-4 Generation Technology Portfolio by Region in the United States. 2-9

Figure 3-1 Primary coolant outlet temperature vs. pressure for lwSMR and GEN IV designs addressed in this report. 3-5

Figure 4-1 ORNL results depicting potentially favorable sites for deployment of SMRs based on multiple siting criteria. 4-9

Figure 4-2 U.S. NRC perspective on continuity of lwSMR and advanced reactor licensing with established LWR licensing basis. 4-15

List of Tables

Table 2-1 The Six Advanced Reactor Concepts Recognized by Generation IV International Forum. 2-6

Table 2-2 Total Estimated Nuclear Energy Investment Needs Over 2010-50 Under the "Two-Degree" Scenario........ 2-10

Table 3-1 Current Generation III Nuclear Reactor Designs, ... 3-2

Table 3-2 Commercially Relevant Small Modular Light Water Reactors (lwSMRs), ... 3-3

Table 3-3 Representative Advanced Generation IV Reactors, ... 3-13

Table 4-1 Overnight costs and levelized cost of electricity for GWe-class LWRs., ... 4-2

Table 4-2 Estimated overnight and electricity costs for SMR and advanced reactor designs. 4-4

Table 4-3 Estimated Funding Required for Demonstration/Prototype Reactors. 4-7

Table 4-4 Illustrative Site Land Area Requirements for lwSMRs and Advanced Reactors. 4-11

Table 4-5 Estimated plant cooling water withdrawals for main steam condenser (m^3/MWh). 4-13

Table 4-6 U.S. Nuclear Regulatory Commission Design Certification for Generation III/III+ Advanced Light Water Reactors. 4-16

Table 4-7 Reported pre-application engagement of lwSMR developers and potential licensees with the U.S. NRC. . 4-17

Table 5-1 Upper bound estimate of potential global lwSMR market assuming favorable economics as an electric power generation option. 5-3

Section 1: Introduction

1.1 Introduction and Context

While construction of new light-water reactors (LWRs) has slowed in the United States (U.S.) over the past several years, new development continues globally, primarily in China and other Asian countries. Also, development of light water Small Modular Reactor (lwSMR) designs is also moving forward in the U.S. and internationally; however, investment and market interest has been softer than anticipated and the ultimate penetration of lwSMRs in the commercial industry remains to be seen.

Meanwhile, an increase in industry and government interest in advanced, non-LWR reactors, has coincided with unprecedented influx of private investment in a growing field of entrepreneurial developers. A primary driver for this renewed interest in non-LWR technology appears to be utility desire for generation options commercially available in the 2030 – 2050 timeframe. As older baseload generation assets, especially coal and nuclear, are removed from their portfolios, new generation options will be needed to meet future energy demands and support a robust business model in the face of uncertain policy, regulatory, and market conditions.

In light of substantial changes in the nuclear generation landscape with respect to lwSMR and advanced reactor technologies, this document provides an update of advanced nuclear generation systems, reflecting the current state and trajectory of the technology, and focusing on six key areas:

- Reactor technology descriptions;
- Economics;
- Siting requirements;
- Regulatory frameworks, design certification and licensing;
- Key markets; and
- Ongoing and future developments.

This document is based on content prepared for the most recent update to the EPRI Technical Assessment Guide (TAG®), [3002006280, Revision 0, September 2016]. EPRI maintains the TAG to keep members informed on the state of technology in power generation and energy storage.

1.2 Background

The earliest phase of commercial nuclear reactor technology deployment for civilian power generation saw many smaller units spanning a wide range of nuclear technology in terms of fuels, coolants, and moderators. In fact, most of the so-called advanced nuclear concepts considered to be GEN IV can trace their roots to one or more demonstration and prototype reactors built and operated in the 1950s and 60s. For example, on December 20, 1951 the first electricity generated by a nuclear reactor came from the Experimental Breeder Reactor EBR-I, a sodium-cooled fast reactor (SFR) located in Arco, Idaho, on what is now the Idaho National Laboratory. The first grid-connected reactor (June 26, 1954) was the Obninsk APS-1 Nuclear Power Station in Obninsk, Russia (then Soviet Union), a demonstration-scale graphite-moderated, water-cooled forerunner to the RBMK design. The first truly commercial nuclear power plant, Calder Hall 1, was a gas-cooled, graphite moderated Magnox demonstration reactor connected to the UK national grid on August 27, 1956. Scale-up of light-water reactor technology originally developed under the U.S. navy propulsion program led to the construction and operation of the Shippingport pressurized water reactor (PWR) in Shippingport, PA (1957), and the Vallecitos boiling water reactor (BWR) in Vallecitos, CA (1957).

1.2.1 Generation I

Further scale-up and commercial deployment of multiple reactor designs spanning LWRs, PHWRs, gas-cooled and high-temperature gas-cooled reactors (GCRs and HTGRs), and SFRs, in the U.S., UK, France, Russia comprised Generation I of nuclear power (Figure 1-1).

Figure 1-1
Evolution of Commercial Nuclear Power Reactor Technology by Generation. [Source: Generation IV International Forum (GIF)][1]

---

[1]Generation IV International Forum (GIF) website https://www.gen-4.org/. Accessed October 2016.

1.2.2 Generation II

In the second phase of commercial nuclear power development, i.e., Generation II (GEN II), ambitious planning for and construction of a nuclear power infrastructure occurred globally. This period, spanning the late 1960s through the 1990s, saw many important trends and events that set the stage for the current nuclear landscape.

Aggressive build rates and increased reactor outputs characterized the United States nuclear power industry during the 1970s:[2]

- 22 reactors were operating and 50 were under construction in 1970;
- New plant orders peaked at 41 in 1973;
- Zion Unit 1 commissioned in 1973 as the first 1000 MWe commercial plant.

U.S. construction trends were mirrored internationally, with brisk construction starts spanning two decades (from 1966 – 1985) peaking in 1976 with 43 new reactor construction projects (Figure 1-2). Over this period, national fleet designs and dominant trends emerged:

- 2/3 PWR and 1/3 BWR technology split in the United States;
- Evolution from GEN I Gas Cooled Reactors (GCRs) to Advanced Gas-Cooled Reactor (AGR) fleet in the United Kingdom;
- Evolution from GCRs to a highly standardized, exclusively PWR fleet in France;
- BWR dominated fleet in Japan;
- Graphite-moderated, water-cooled reactors (RBMKs) followed by pressurized water reactors (VVERs) in Russia (then Soviet Union).

The GEN II period was punctuated by two severe accidents occurring in 1979 at Three Mile Island Unit 2 and in 1986 at Chernobyl Unit 4. The two accidents represented two extremes with respect to the technologies involved (PWR vs. RBMK) and the offsite consequences (none vs. massive land contamination with long-term relocation of affected populations). However, both led to important changes in the commercial nuclear industry outcomes with respect to establishment of formalized self-regulation for improved performance and safety of nuclear power industry. In the United States, the Institute of Nuclear Power Operations (INPO) was established in December 1979 following Three Mile Island. The World Association of Nuclear Operators (WANO) established in 1989, as a direct response to Chernobyl accident.

---

[2] G. Vine. 2015. Abridged History of Reactor and Fuel Cycle Technologies Development: A White Paper for the Reactor and Fuel Cycle Technology Subcommittee of the Blue Ribbon Commission. March 15, 2011.

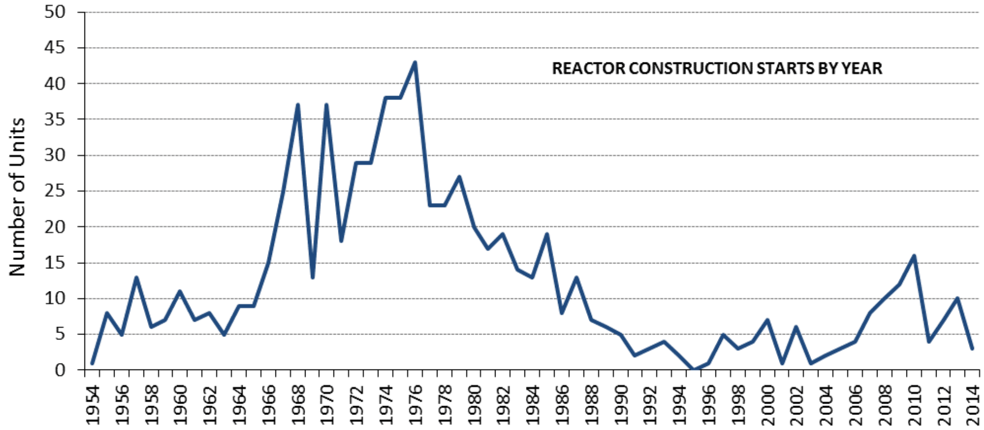

Figure 1-2
Construction Starts for Nuclear Reactors Worldwide. [Source: IAEA 2015. Nuclear Power Reactors in the World, Reference Data Series No. 2, 2015 edition. http://www-pub.iaea.org/books/IAEABooks/10903/Nuclear-Power-Reactors-in-the-World-2015-Edition]

A massive wave of cancellations of nuclear plant order and construction projects began in the late 1970s and extended into the 1980s primarily as a result of unfavorable political and market conditions also exacerbated by aftermath of the Three Mile Island accident.[3] By the end of Generation II construction in the United States, the market for new nuclear in the U.S. essentially disappeared as cost overruns and schedule delays had become endemic for U.S. nuclear construction projects and electricity demand growth was being met with power up-rates in the nuclear sector and with other generation sources, demand side management, and improvements in efficiency. Globally, some new nuclear construction continued through the 1980s and 90s, while the 2000s through 2015, nuclear construction appears to be accelerating, particularly in Asia.

Note: Advanced Reactors are commonly classified as Generation IV (GEN IV) reactors, and the terms are frequently used interchangeably. In this report, the more general term 'advanced reactor' is used preferentially to describe reactor designs beyond Generation III/III+ and lwSMRs, and which provide compelling advantages over currently available designs in terms of safety, performance, and/or economics.

[3] The tally of cancelled generation projects in the United States included 97 nuclear units and 75 coal plants. As of 2015, construction of all operating US plants began before 1975. TVA's Watts Bar Unit 1 was the last U.S. plant to enter service in 1996. Construction on Watts Bar Unit 2 was suspended in 1985 but resumed in 2007. Commissioning of Watts Bar 2 was in 2016 and now the reactor is connected at the grid and operating full power.

Section 2: Nuclear Generation Role

2.1 Nuclear Generation Current Share of Electricity Mix

Nuclear accounts for 11% of world power generation with 396 GWe of installed capacity in 2014[4], down from 1996 peak of 18%. This contribution is expected to rise again in the near-future as substantial capacity is added in Asia. In the US, nuclear continues to contribute just under 20% of electricity (19% in 2014)[5], but a tepid new build and retirement of aging operating reactors threaten the role of nuclear in the United States. Significant numbers of subsequent license renewals extending operation to 80 years and a more aggressive new build program will be needed to avoid a steep decline in nuclear generation on the order of 70% over the 2035 – 2045 timeframe.

Of the world's operational grid-connected nuclear plants in 2013, the vast majority (82%) are light-water reactors (LWRs)[6], i.e., designs employing ordinary "light" water for cooling, heat transfer and neutron moderation, and use current nuclear fuel technology based on metal-clad uranium oxide. Overall, 96% are water-cooled designs, including pressurized heavy water reactors (e.g., CANDUs) and light-water cooled graphite moderated reactors (e.g., RBMKs).[7] Most of these are large (500 – 1000+ MWe) units built to take advantage of economies of scale and to provide baseload power generation.

2.2 Future Role for Nuclear Generation

The future outlook and role for nuclear generation varies widely by country and is heavily dependent on market, policy, and regulatory drivers. The operating reactors represent a substantial technology basis, predominately Gen II LWRs, on which further expansion and deployment of new nuclear technologies will be established. Continued operation of Generation II reactors and even limited introduction of Generation III/III+ and lwSMRs provide an important bridge to construction and operation of advanced designs and expansion of commercial nuclear technology into new missions and markets by maintaining key

---

4 IEA World Energy Outlook, 2015. http://www.worldenergyoutlook.org/media/weowebsite/2014/WEO2014FactSheets.pdf

5 USEIA, 2015. http://www.eia.gov/todayinenergy/detail.cfm?id=21072

6 WNA, 2015. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Advanced-Nuclear-Power-Reactors/

7 IAEA, 2013. Nuclear Power Reactors in the World. Reference Data Series No. 2. http://www-pub.iaea.org/MTCD/Publications/PDF/rds2-33_web.pdf

institutions and infrastructures, even if at reduced scales. Such assets include industrial, regulatory and financial infrastructures, human capital in the form of experience and expertise, and specialized nuclear-grade supply chains.

Operating nuclear plants also provide the majority of low-carbon generation capacity in the United States and other countries. Planning scenarios for future electricity generation portfolios frequently assume continued operation of the existing nuclear fleet beyond current license periods (e.g., 80% to 80 years)[8] in order to meet future energy demands and satisfy a range of possible carbon constraints for power plant emissions. Long term operations of nuclear plants are being evaluated and represent a technical challenge on its own. Likewise, a simple one-for-one replacement formula of retiring reactors in the United States also represents a substantial challenge due to the number (99 as of 2015) and the relatively short timeframe over the fleet reaches the end of the first license extension period – 60 years.

In the 2000s, the United States was poised for a so-called "Nuclear Renaissance" that did not materialize due to the confluence of multiple unforeseen developments that include the rapid emergence of shale gas, reduced growth in electricity demand accompanying economic recession in late 2000s, increasing penetration of subsidized wind and solar generation, and unfavorable pricing structures in unregulated electricity markets. Likewise, nuclear growth in Western Europe has also been modest.

The March 2011 accident at Fukushima Daiichi had major impacts on the near-term nuclear future in several countries. The impacts were understandably greatest in Japan itself where all reactors were shut down for an extended period while new regulatory authority and regulations were put in place. Restart of the current Japanese fleet began in September 2015 and will proceed at a deliberate pace; many will not restart due to economic viability concerns and fundamental safety issues linked in many cases to new seismic concerns. In Germany, the decision has been made to transition completely away from nuclear power with shut down of all plants by 2022 with the revival of an earlier nuclear phase-out plan.[9] The rest of the operating nuclear commercial fleet worldwide, suffered economic and licensing pressured, triggered by the implementation of new safety upgrades demanded by post-Fukushima licensing requirements.

However, the outlook is not gloomy everywhere. In fact, there is a healthy market for new nuclear in Asia, and expressions of interest by many countries that are new to nuclear. As of 2015, a total of 60 commercial nuclear reactors were under construction, representing 59 GWe of new generation (Figure 2-1).[10] In light of continuing electricity demand globally and increasing pressure for low

---

[8] PRISM 2.0: The Value of Innovation in Environmental Controls - Summary Report. EPRI, 2012. 1026743.

[9] WNA, 2015. Nuclear Power in Germany. Updated August 2015. http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Germany/

[10] IAEA PRIS Database, 2016. https://www.iaea.org/PRIS/WorldStatistics/UnderConstructionReactorsByCountry.aspx

emission generation sources, both for future climate change and nearer term environmental quality concerns, robust growth in nuclear generation capacity is projected for a range of economic, policy and regulatory conditions. For example, under the Organization for Economic Cooperation and Development (International Energy Agency (OECD/IEA) scenario for limiting global warming to 2 °C through de-carbonization of all energy sectors, the overall global capacity of nuclear more than doubles from just under 400 GWe in 2015 to approximately 930 GWe in 2050 (Figure 2-2). Generation capacity from nuclear remains flat in the OECD countries (including the United States and European Union), while the majority of the increase is seen in China, India, the Middle East and Russia. However, even flat growth in nuclear in developed economies could still involve substantial installation of new nuclear capacity if existing generation is retired and requires replacement.

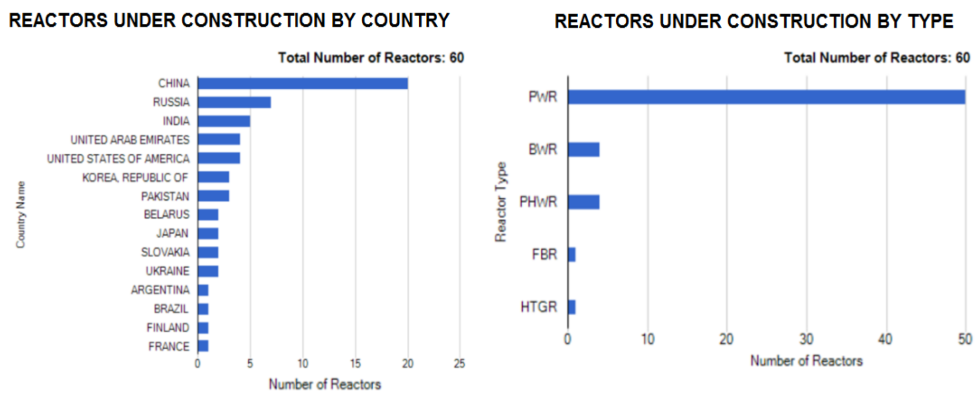

Figure 2-1
Snapshots of New Commercial Nuclear Reactors under Construction Worldwide by Country (LEFT) and by Type (RIGHT). [Source: IAEA PRIS Database. Updated 10 Oct 2016.
https://www.iaea.org/PRIS/WorldStatistics/UnderConstructionReactorsByCountry.aspx]

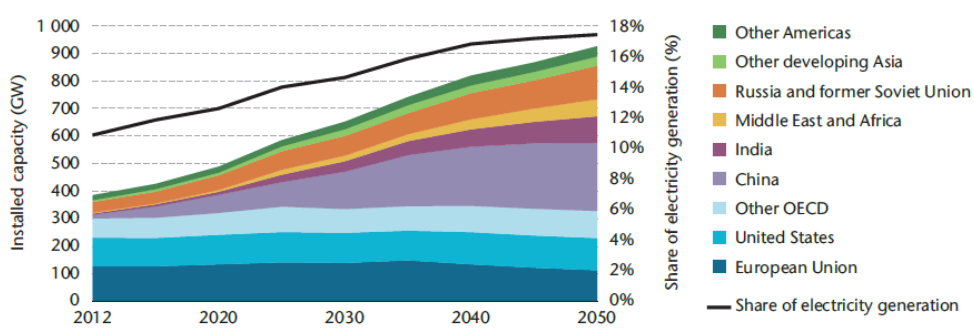

Figure 2-2
Projected Nuclear Generation Capacity (GWe) and Contribution (%) to Global Total under the Two Degree Temperature Rise Scenario (2DS). [Source: IEA 2015. Technology Roadmap. ©OECD/IEA 2015 Technology Roadmap, *IEA Publishing.]*

2.3 Technology Options for New Nuclear Generation

Near-term options for introduction of new nuclear capacity are still dominated by large GEN II and Generation III LWRs and the latest pressurized heavy water reactor (PHWR) designs. Light water SMR deployments within the next decade also appear feasible given recent levels of interest and the fact that two units are under construction. Meanwhile, many Generation IV design concepts and variants are being proposed and developed, targeting 2035 and beyond for first commercial deployments. While operational experience is limited and commercial performance has been historically poor for most non-LWR reactor classes, substantial interest and investment in GEN IV may lead to several commercial options being available in the 2030s and 2040s when substantial capital investment will be made for replacement and new generation capacity, and at least on country appears on track to fully commercialize a GEN IV reactor in the next decade, i.e., China with the modular HTR-PM system (see Table 2-1).

2.3.1 Generation III

Generation III nuclear reactors incorporate evolutionary design improvements on prior commercially deployed technologies based on the substantial operational experience accumulated over five decades. The motivation for industry development of a new technology generation came from the electric utilities who were facing many challenges as nuclear owner/operators in the early 1980s. In 1983, an EPRI survey of nuclear utility executives asked what attributes would enable reconsideration of new nuclear plants. The responses prioritized designs that were:

- safer and simpler;
- competitive;
- standardized; and
- pre-licensed by the U.S. NRC.

EPRI initiated work in 1985 on a set of utility requirement to establish framework for advanced light water reactors (ALWRs) to provide the industry with a:

- stabilized regulatory basis for new technologies;
- standardized set of requirements for use in design certification; and
- standardized set of requirements for future owner bid packages.

The resulting Utility Requirements Document (URD)[11] is now in its 13th revision and spawned a similar effort tailored for the European market – the

[11] A publicly available version of the URD, Vol. 1 (Rev. 2) from 1999, provides example of structure, policies and top-tier design requirements. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=TR-016780-V1R2

European Utility Requirements Document (EUR). In concert with the URD development, there was also a major collaborative effort and investment by the U.S. government-and industry that resulted in the development of new Generation III/III+ advanced light water reactor (ALWR) designs, including those with active safety systems (GEN III), e.g., GE-Hitachi/Toshiba ABWR and AREVA EPR, and passively safe designs (GEN III+), Westinghouse AP-1000 and GE-Hitachi ESBWR. The paradigm shift pursuing safety and economy through design simplicity and standardization reestablished a market and role for large nuclear generation in the 21st century.

2.3.2 Small Modular Reactors (SMRs)

Contemporary challenges associated with constructing large nuclear include several scale-dependent factors such as overnight capital cost, construction duration and financing and grid capacity constraints (e.g., for replacement of smaller fossil generation). Small Modular Reactors are intended to overcome many of the obstacles currently facing large GWe class nuclear plants with smaller plants that represent reduced financial risk per unit (capital cost), better match generation capacity and grid connection of older, smaller coal generation stations, and offer potential improvements in economics and licensing through assembly-line style manufacturing. This pursuit of smaller unit generation capacity represents a stark reversal of the historical trend toward larger plants seen over the evolution from Generation I through III. The term small modular reactor (SMR) generally applies to reactor designs with power outputs below 300 MWe and featuring modular-based construction and assembly, i.e., factory-based manufacturing and transportable to the site for assembly. Many SMRs are pressured water reactors (PWRs), and use of the term SMR commonly implies the small integral[12] PWR designs that dominate the current landscape and will likely comprise the first wave of SMR deployment, given the many similarities to current operating reactors. For example, some are designed to accept standard commercially available 17x17 PWR fuel assemblies. In this report, use of the term lwSMR refers to these small modular LWRs.

SMRs with outputs under 50 MWth and/or 20 MWe are often designed as "nuclear battery" concepts. These generally feature simplified operation, robust performance, minimal maintenance, "walk away safe" passive safety attributes, long core life-times and no onsite refueling. The refueling and core maintenance philosophy is essentially that of a cartridge or battery, i.e., removal intact and return to manufacturer and followed by replacement with a fresh module, much in the same way fuel assemblies are managed in current LWRs.

Another class of SMRs are those that use other working fluids for cooling and heat transfer, including gases, liquid metals, and molten salts. These non-light-water SMRs generally fall under the designation of Generation IV (GEN IV) advanced reactors. In addition to new coolants, these next generation designs

[12] Small modular PWRs with steam generators located inside the reactor pressure vessel.

offer various combinations of new attributes that can include near ambient operating pressures, high outlet temperatures, product flexibility, strong negative feedback, inherent safety features and fast neutron spectra. In this report, these reactor designs are referred to as non-light water SMRs and/or Generation IV reactors.

2.3.3 Generation IV – Advanced Reactors

Generation IV reactors are generally understood to be fission reactor designs that offer significant improvements with respect to current nuclear technologies in terms of potential for enhanced resource utilization, inherent safety, economics, product flexibility (process heat generation, hydrogen production, medical isotopes production, etc.), are scalable and offer proliferation resistance and security. Strictly speaking, the term Generation IV refers to the six advanced reactor design classes designated under the Generation IV International Forum (GIF).[13]

Table 2-1
The Six Advanced Reactor Concepts Recognized by Generation IV International Forum.

Reactor Concept	Coolant	Outlet Temperature (°C)	Pressure	Neutron Spectrum
Gas-cooled fast reactor (GFR)	Helium	850	High	Fast
Lead-cooled fast reactor (LFR)	Pb (metal) or Pb-Bi (eutectic)	500 - 800	Low	Fast
Molten salt reactor (MSR)	Fluoride salts	700 - 1000	Low	Fast or Thermal
Sodium-cooled fast reactor (SFR)	Sodium (metal)	500 - 550	Low	Fast
Supercritical-water-cooled reactor (SCWR)	Water	500 - 625	Very High	Fast or Thermal
Very-high-temperature reactor (VHTR)	Helium	700 - 1000	High	Thermal

The SMR designation applies to many of the proposed advanced GEN IV reactors concepts as most have equivalent electrical outputs that fall (or readily scale) below the nominal 300 MWe limit and are compatible with the modular paradigm in terms of design, manufacture, and deployment.

[13] *A Technology Roadmap for Generation IV Nuclear Energy Systems*. GIF-002-00. 2002.

2.4 Challenges and Opportunities for New Nuclear

The role for nuclear is challenged by changing energy markets, increasing competition from other generation sources and paradigms, and evolving demands for existing energy infrastructures. With these challenges come new opportunities for realizing the value of nuclear generation by way of its unique attributes.

2.4.1 Uncertainty

Looming fleet wide retirement of large baseload generation through 2050 presents a major challenge for utilities in the United States and other developed economies with large, aging energy infrastructures (Figure 2-3).

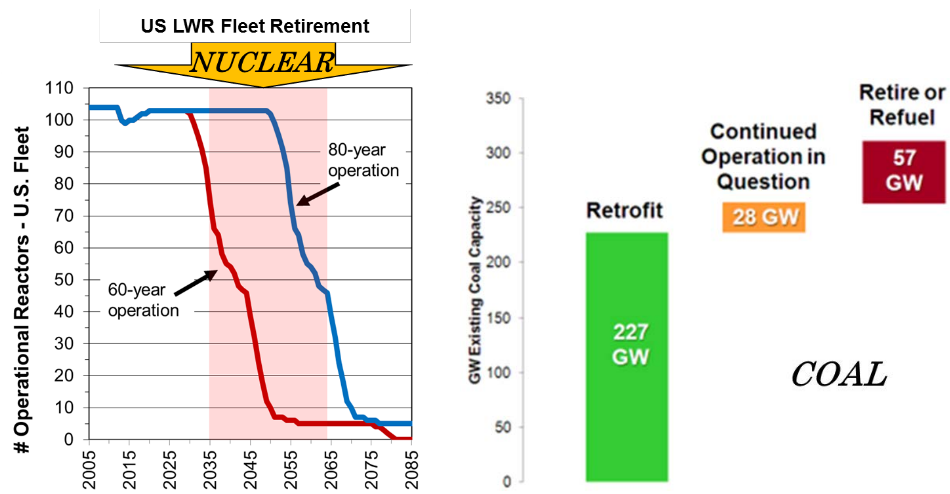

Figure 2-3
Generation Capacity at Risk in the United States over the Next Three Decades. LEFT – Retirement of U.S. Nuclear Fleet for 60- and 80-Year Lifetimes. [Source: USNRC 2013] RIGHT – Near-Term Retirement of U.S. Coal Fleet for the Evolving Economic and Regulatory Environment. [Source: PRISM 2.0: The Value of Innovation in Environmental Controls - Summary Report. EPRI, 2012. 1026743.[14]]

Assuming all operating reactors in the United States apply for and receive license extensions to 60 years, retirement of 90% of the fleet could occur over a two-decade period, which is very short given the scale of investment and construction to just perform one-for-one replacement. A second extension to 80-year

[14] Projections assume reference natural gas price for 2010-2035 of $6.50/MMBtu. Retrofits do not include CCS; however, assumed lack of new coal units beyond those under construction results from high uncertainty in future federal and state regulations, including carbon constraints.

operation would obviously provide an additional 20-year grace period for construction and commissioning of new generation assets. In addition to nuclear, early retirement of coal generation due to economics and increasing environmental standards could see a loss of approximately 60 – 90 GWe in the United States alone.

Planning for such major capital investment in new generation capacity requires long lead times and the accompanying large uncertainties of energy and climate policy (and their translation into regulation and market drivers). Availability of low carbon, energy dense generation options that are deployable on commercially relevant scales and timeframes can mitigate the business risk associated with uncertainty in the power sector globally.

Even for relatively modest projections for electricity demand growth, natural gas prices, and carbon regulation, projections indicate an important role for nuclear generation in addressing future capacity demands. And regional differences within a large, fragmented energy market like that of the United States can exacerbate the need for new nuclear, as shown in the portfolio generated for the southern U.S. (Figure 2-4). With limited penetration of wind, solar and other new low-emission generation, load growth in the South is met with over 50 GWe of new nuclear capacity (light grey wedge) installed by 2050 while maintaining 80% of existing LWRs operating to 80 years (dark grey wedge). While 50 GWe of new nuclear is probably not attainable, the magnitude does signal a strong regional role for nuclear where alternatives are not available or practical.

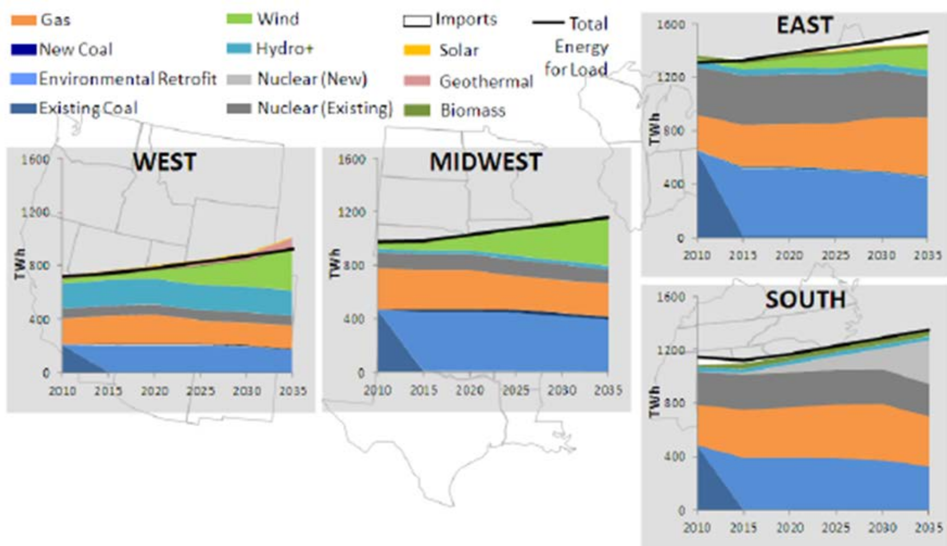

Figure 2-4
Generation Technology Portfolio by Region in the United States. [Source: PRISM 2.0: The Value of Innovation in Environmental Controls - Summary Report. EPRI, 2012. 1026743.[15]]

2.4.2 Investment to Replace Retiring Assets

The scale of investment needed to replace aging energy infrastructure is immense, measured in $ trillions (USD). Investment need for energy infrastructure in general in the United States is projected to be $2 trillion (USD) over next 10 years. Globally, the figure is an estimated $1 trillion (USD) per year. The IEA concluded in its 2014 special report, World Energy Investment Outlook, that $48 trillion in global investment is needed through 2035 to meet projected energy needs, of this total nuclear represents $1 trillion (USD).[16] An additional 10% is needed to establish a path to the 2DS climate stabilization goals through reduced carbon emissions (Figure 2-2).

While nuclear represents a small fraction of the total world's energy infrastructure investment, the sums remain substantial (Table 1-2). For example, the IAE projection 930 GWe of installed nuclear capacity by 2050 for climate stabilization corresponds to a global investment of $4.4 trillion (USD).[17] This scale of potential investment indicates a commensurate level of investment in research, development and demonstration (RD&D) efforts will be needed to

---

[15] Projections assume reference natural gas price for 2010-2035 of $6.50/MMBtu. Retrofits do not include CCS; however, assumed lack of new coal units beyond those under construction results from high uncertainty in future federal and state regulations, including carbon constraints.

[16] IEA 2014. World Energy Investment Outlook. http://www.iea.org/publications/freepublications/publication/WEIO2014.pdf

[17] NEA/IEA, 2015. Nuclear Energy Technology Roadmap.

advance the commercial maturity of new nuclear generation options in order for them to be available on the scale and schedule needed.

Table 2-2
Total Estimated Nuclear Energy Investment Needs Over 2010-50 Under the "Two-Degree" Scenario. [Source: OECD/IEA and OECD/NEA 2015. Nuclear Energy Technology Roadmap.]

Country/region	$ Billions (USD)
United States	713
European Union	704
Other OECD	577
China	1,025
India	412
Middle East and Africa	303
Russia and former Soviet Union	548
Other developing Asia	153
Other Americas	25
World	4,473

2.4.3 Private Sector Interest and International Partnerships for Nuclear Investment

In the United States, another new opportunity for commercialization of lwSMRs and GEN IV reactors comes in the form of private capital. This has been attributed in part to a new generation of wealthy investors that were entrepreneurs themselves and have come to investing with more philanthropic goals. One account reports a total of 55 nuclear startup companies representing a combined $1.6 billion in private venture capital funding.[18] However, financial markets via lenders and bondholders, remain the primary source of financing for the near-future. Meanwhile, outside of the United States, international partnerships and sovereign financial backing has emerged as the dominant model for funding nuclear projects.[19]

---

[18] Fortune.com, July 6, 2015. How Startups Can Save Nuclear. http://fortune.com/2015/07/06/how-startups-can-save-nuclear-tech/

[19] W.S. Howes. Nuclear Power, Finance and the Capital Markets. Presentation at the Nuclear Infrastructure Council's Advanced Reactor Technical Summit II, February 11-2, 2015. Lowell, MA.

2.4.4 Access to New Markets via New Products and Applications

Product diversification and expansion into new markets are important strategies for countering declining revenues and threats to the traditional electric power business model through baseload generation.[20] Novel attributes of lwSMRs and GEN IV reactors potentially offer owner/operators with an option-rich future through greater flexibility in terms of operation, deployment and products not otherwise appropriate for larger Generation III reactors. Light waterSMRs offer access to new markets and applications such as remote, island and micro-grid power generation; improved capacity matching and load following for grid support, and as replacement for smaller coal-fired units having existing but limited grid connections.

To these benefits, GEN IV systems add a number of possible missions that have either been limited to fossil generation or not possible with available technology. These include:

- Medical Radioisotopes production;
- Extension of natural resources through high conversion and breeding of new fuel; and
- Industrial process heat and poly-generation

The ability to achieve higher outlet temperatures, i.e., in the 500 – 1000 ˚C range (vs. 300 ˚C for LWRs) will drive higher thermal efficiencies, including the use of Brayton-cycle power conversion, and substantially expands the non-electricity generation applications for nuclear, e.g., more efficient and cost effective water desalination and industrial-scale production of hydrogen. These two products offer potentially valuable commodities and means for practical energy storage during periods when electricity prices are unfavorable. Access to fresh water is already an acute issue in many parts of the world and large-scale trading of potable water as a commodity is widely anticipated.[21] Meanwhile, the potential for hydrogen to displace liquid fuels and leap frog battery technology as a dominant energy carrier for transportation would bring access to a new energy market that rivals electricity in scale. As the world's leading consumer of battery technology, Toyota has already made a very public bet on hydrogen fuel cycle technology as a future for the automotive industry.[22]

---

[20] Polygeneration: An Opportunity for Diversification and New Revenue. EPRI. 2013. 3002002215. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002002215

[21] P. Domm. Why Trading Water Futures Could be in Our Future? CNBC.com, 2 July 2014. http://www.cnbc.com/2014/07/02/why-trading-water-futures-could-be-in-our-future.html

[22] Toyota Mirai marketed as "…the world's first fuel cell vehicle for the mass market." http://www.toyota-global.com/innovation/environmental_technology/fuelcell_vehicle/

2.4.5 Clean Slate for Emerging Energy Markets

Technology leapfrogging has been cited as a fast track to economic growth in developing countries where prior technologies have not been widely adopted and therefore the sunk costs and associated inertia do not exist.[23] Adoption of wireless communications technology in lieu of wired infrastructure is a commonly cited example. Accordingly, it may be feasible for countries and regions lacking an established legacy energy infrastructure to make choices that would not be practical in the near term for most developed economies, such moving away from central station generation and national-scale electricity grids. With these "clean slate" choices come new or unique opportunities for smaller, more flexible energy generation offered by lwSMRs and many of the advanced GEN IV reactor concepts.

---

[23] M.W.L. Fong. 2009. Technology Leapfrogging for Developing Countries. IGI Global. 2009. Accessed at: http://journalistsresource.org/wp-content/uploads/2013/04/Technology-Leapfrogging-for-Developing-Countries.pdf

Section 3: Reactor Technology Descriptions

While the focus review is on lwSMRs and related GEN IV technology developments, it is useful for context to briefly summarize current Generation III/III+ designs that are available or under development for the world nuclear marketplace. Coverage of reactor technology is then divided between the light water SMRs and non-LWR Generation IV reactors. For each group, high level design of representative designs are provided, followed by discussions on markets, regulatory/licensing considerations and economics that are specific to each group. More general, cross-cutting aspects of lwSMR and GEN IV reactor licensing, construction and operation are addressed in Section 3 below.

3.1 Generation III/III+

The focus of this update is on lwSMRs and related GEN IV technology developments. However, for completeness, Table 3-1 summarizes current GEN III designs available or under development for the world nuclear marketplace.

3.2 Small Modular Reactors

All light water SMRs considered here are PWRs and target electricity generation as the primary business case, although other missions such as desalination, deployment on the same site where coal-fired generation units were decommissioned, and district heating are feasible and occasionally mentioned by developers. Globally, there are a number of small modular LWR designs being offered. Table 3-2 lists the most prominent and commercially relevant designs in terms of organizational backing and readiness for deployment within 10 years.

Table 3-1
Current Generation III Nuclear Reactor Designs[24,25]

Developer / Vendor	Design	Country	Type	Electrical Output per Unit (MWe)	In Operation*	Under Construction*
AREVA	EPR	France	PWR	1,600	0	4 (Finland, France, China)
AREVA/MHI	ATMEA	France/ Japan	PWR	1,100	0	0
CANDU Energy	EC6	Canada	PHWR	700	0	0
CNNC-CGN	Hualong-1	China	PWR	1,100	0	1 (China)
GE-Hitachi/ Toshiba	ABWR	US/ Japan	BWR	1,400 – 1,700	4 (Japan)	4 (Japan, Taiwan)
GE-Hitachi	ESBWR	US	BWR	1,600	0	0
KEPCO/KHNP	APR1400	Korea	PWR	1,400	0	7 (Republic of Korea, UAE)
Mitsubishi	APWR	Japan	PWR	1,700	0	0
ROSATOM/ Gidropress	AES-92, AES-2006	Russia	PWR	1,000 – 1,200	1	10 (Russia, Belarus, China, India)
SNPTC/SNERDI	CAP1000, CAP1400 CAP1700	China	PWR	1,200 – 1,700	0	0
Westinghouse/ Toshiba	AP1000	US/ Japan	PWR	1,200	0	8 (China, USA)

[24] IEA/NEA, 2015 Nuclear Energy Technology Roadmap.

[25] WNA, 2015. Advanced Nuclear Power Reactors. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Advanced-Nuclear-Power-Reactors/

Table 3-2
Commercially Relevant Small Modular Light Water Reactors (lwSMRs)26,27

Developer / Vendor	Design	Country of Origin	Type[a]	Electrical Output per Unit (MWe)	No. under construction
BWXT	mPower	United States	iPWR	180	0
CNNC	ACP100	China	PWR	100	0
CNEA	CAREM	Argentina	iPWR	25	1 (Argentina)
Holtec	SMR-160	United States	PWR[b]	160	0
KAERI	SMART	South Korea	iPWR	100	0
NuScale Power	NuScale	United States	iPWR	50	0
OKBM Afrikantov	KLT-40S	Russia	PWR	35	2 (Russia)[c]
OKBM Afrikantov	VBER-300	Russia	PWR	325	0
SNPTC/SNERDI	CAP-200	China	PWR	200	0
Westinghouse	W-SMR	United States	iPWR	225+	0

[a] iPWR refers to integral pressurized water reactor design.

b Holtec considers its design to be an integral PWR; however, the steam generator and pressurizer are external to the reactor pressure vessel, directly connected (no piping) in an offset configuration.

c Twin-units deployed on a floating barge.

[26] *Nuclear Energy Technology Roadmap: 2015 Edition*. OECD/IEA and OECD/NEA. Paris. 2015.

[27] WNA, 2015. Advanced Nuclear Power Reactors. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Advanced-Nuclear-Power-Reactors/

Small LWRs are not new. The first generation of commercial power reactors included many smaller designs. And there have been a number of small LWRs have been deployed around the world for various non-commercial applications; the United States built and operated several versions for land- and barge-based power generation.[28] What is new is the focus on modular design that enables factory-based manufacturing, transportation via normal modes including truck and rail, short construction timelines, and incremental deployment. These features offer utilities lower-cost and scalable deployment of generation to address prohibitive capital cost and restrictive siting requirements (e.g., grid connection and cooling water resources).

Also new is the emphasis on integral PWR (iPWR) designs, in which primary system components (i.e., reactor core, control rod drive mechanisms, steam generator and pressurizer) are contained within a single pressure vessel. As a result, overall complexity is reduced with positive consequences for safety. Without the need for large-diameter piping, large-break loss-of-coolant accident (LOCA) scenarios are eliminated. Likewise, the severity of small-break LOCAs is reduced. And the compactness and simplicity of the primary system also facilitates the use of passive cooling approaches (e.g. air condensers) for normal operations and safety functions. Other design attributes common to most contemporary lwSMR and advanced reactor designs include underground vault construction and seismic isolation, which offer greater protection against external threats and hazards like aircraft impact and earthquakes.

Many positive and negative attributes of each reactor systems are driven by the choice of the primary system coolant or working fluid, as these fundamental characteristics drive economics, material performance, safety, and overall system complexity and cost. Figure 3-1 depicts the pressures and temperatures of the systems described in this update. BWRs and PWRs operate around 300 ˚C and high pressures, i.e., 7.6 and 15.5 MPa respectively. Higher temperatures generally yield higher thermal efficiencies and potential access to more advanced power conversion cycles (e.g., supercritical-CO2 Brayton cycles) and non-electric markets (hydrogen production, chemical industry applications, desalinization, etc.). Lower pressures should lead to less costly primary system components and less energetic accident scenarios.

---

[28] Big Rock Point, a Generation I 67 MWe BWR, operated for 35 years as a commercial power reactor in Michigan. The U.S. Army commissioned and operated the 10 MWe PWR MH-1A from on board a converted Liberty ship renamed *Sturgis* that was towed to the Panama Canal Zone and supplied power from 1968 to 1977. A number of other small land and barge based reactors were constructed under the U.S. Army Nuclear Power Program. *Office of the Deputy Administrator for Defense Programs (January 2001),* Highly Enriched Uranium: Striking A Balance - A Historical Report On The United States Highly Enriched Uranium Production, Acquisition, And Utilization Activities From 1945 Through September 30, 1996 (Revision 1 (Redacted For Public Release) ed.), U.S. Department of Energy, National Nuclear Security Administration. Available at: http://www.fas.org:8080/sgp/othergov/doe/heu/.

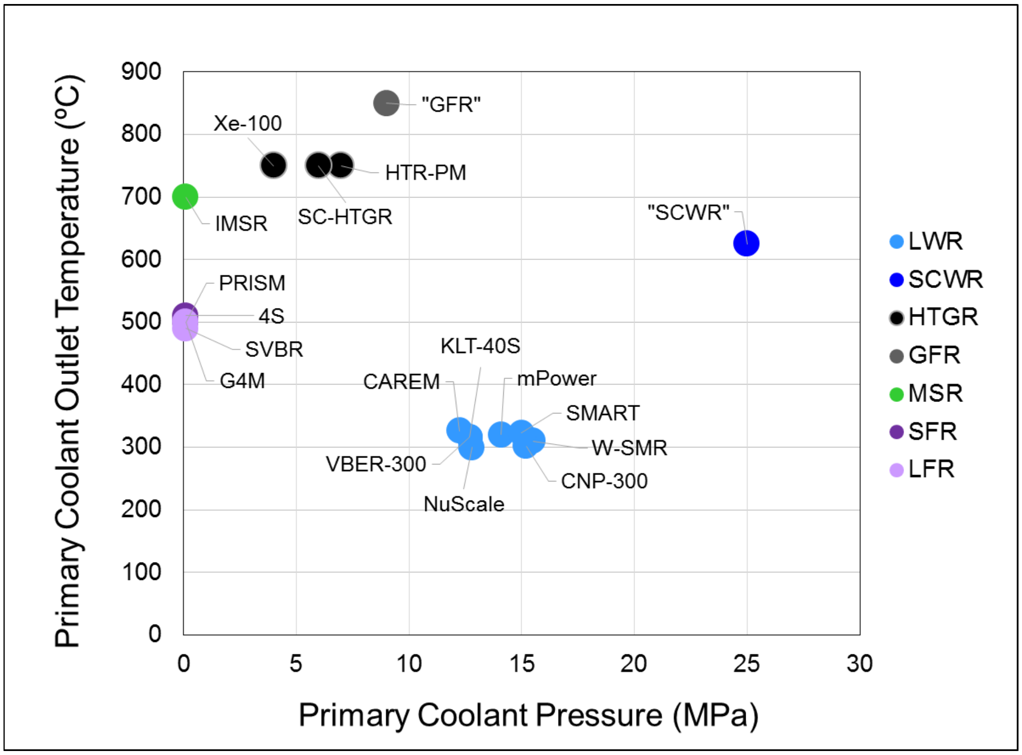

Figure 3-1
Primary coolant outlet temperature vs. pressure for lwSMR and GEN IV designs addressed in this report.

3.3 US Small Modular Reactor Designs

The United States has driven development of smaller LWRs, and the four U.S. lwSMR designs in Table 3-2 are sufficiently developed and backed by established organizations to be considered as credible options for deployment within the next decade with continued investment in design and licensing. These designs are offered by Babcock &Wilcox Technologies (BWXT), NuScale, Holtec, and Westinghouse.

3.3.1 BWXT mPower

The mPower reactor is a 180 MWe integral PWR being developed by Generation mPower LLC, a joint venture of Babcock & Wilcox Technologies and Bechtel. The mPower units are designed to be deployed in pairs within one shared reactor building, each having its own containment structure. The Reactor Pressure Vessel (RPV) envelopes primary system components: fuel, control rod drive mechanisms, steam generator, pressurizer and reactor coolant pumps (and AC Power). The reactor is designed to use current commercially available PWR fuel designs (UO2 – Zr fuel/cladding system) on a four-year, once-through fuel cycle. The reactivity control eliminates the use of soluble boron during normal operations and is reported to provide greater maneuverability for improved load following capabilities. The plant is designed for safe shutdown after design basis accidents without operator intervention for at least 72 hours; a 14-day coping time without offsite or onsite AC power is reported. The commercial case for the mPower lwSMR includes localized sourcing and manufacturing of all components within the United States and transportation of the intact RPV by truck or rail to any accessible location.

Until early 2014, mPower appeared to be leading the race toward lwSMR design certification, licensing and construction in the United States. The company teamed with the Tennessee Valley Authority (TVA) to pursue construction of up to six units at the Clinch River site near Oak Ridge, Tennessee. B&W mPower became the first recipient of a major DOE funding award for lwSMR commercialization in 2012, with $79 million cost-share awarded in 2013 for design and licensing along with potential access to over $200 million in additional matching funding in out years. However, mPower scaled back its own annual spending to $15 million in 2014 after failing to secure the desired level of support and interest from other customers and investors, and then executed a spin-off, by consolidating all nuclear technologies (mPower included) as part of the newly created BWXT. As a result, DOE funding has been withdrawn and mPower is continuing with a more modest R&D program.[29,30,31]

3.3.2 NuScale Power[32]

The NuScale Power Module is a 50 MWe reactor designed for modular, scalable deployment for up to 12 units installed per plant. Therefore, a nominal 600 MWe plant could be incrementally deployed over time through addition of individual NuScale Power Modules (NPMs). Refueling, maintenance and inspection of individual units is conducted while other modules continue to operate, which offers the opportunity to keep a large generating capacity online as opposed to the case for single-unit plants. Similarly, this 50 – 600 MWe range provides potentially greater deployment flexibility. NuScale deliberately sized the primary system to allow factory construction of the NPM unit, which includes the containment vessel. As the largest component, the NPM is designed for intact transport to all accessible sites by truck, rail and barge.

The NuScale design exclusively relies on natural circulation for core cooling during normal operation and off-normal conditions, eliminating the need for reactor coolant pumps. Each NPM is designed to enter safe shutdown for station blackout conditions with no required backup power, no operation intervention, and no makeup water for cooling. Actuation of emergency core cooling relies on operation of a few safety-related valves. As part of a multi-unit plant, the power modules are deployed in a large common water-filled pool constructed below

---

[29] J. Halfinger. *The mPower SMR: A practical option for the global energy industry*. Nuclear News, December 2014. P 58-59.

[30] SMR funding signed, sealed and delivered. World Nuclear News. 16 April 2013.

[31] *Funding for mPower reduced*. World Nuclear News. 14 April 2014.

[32] M. McGough. *NuScale Power: One year after the DOE award*. Nuclear News. December 2014. p. 60-62.

ground. If AC power is lost, the pool serves as an intermediate heat sink with high thermal inertia and, with passive rejection of pool heat load to the environment, offers virtually unlimited cooling capacity for all power modules.

NuScale has assembled a strong industrial team, providing resources and experience supporting design development toward certification and eventual licensing for construction and operation. Major partners include Fluor Corporation, Rolls-Royce, Ultra and ENERCON.[33] NuScale has also forged a path toward a customer base with the 2013 launch of the Western Initiative for Nuclear (WIN) as regional collaboration among potential customers and stakeholders for the technology in the western United States. Under the WIN framework, Utah Associated Municipal Power Systems (UAMPS) stepped forward to become the first NuScale plant owner, partnering with Energy Northwest as the nuclear operator. Site selection is focused on a location within the DOE's Idaho National Laboratory reservation.[34,35]

NuScale won the second of two DOE cost share awards in 2013, with up to $217 million in matching funds over five years. Following the slowdown in the mPower effort, NuScale now represents the only active participant in the DOE lwSMR program. NuScale intends to submit an application for USNRC design certification by the end of 2016. Potential owner UAMPS plans to submit its construction and operation license application (COLA) in the late 2017 or early 2018 timeframe. With these developments in hand, NuScale appears to be on track toward deployment of the first commercial lwSMR in the United States.

---

[33] http://www.nuscalepower.com/

[34] *Federal funding agreed for NuScale*. World Nuclear News. 29 May 2014.

[35] *NuScale SMR licensing schedule outlined*. World Nuclear News. 2 July 2015.

3.3.3 Holtec Inherently-Safe Modular Underground Reactor (HI-SMUR SMR-160)[36]

The HI-SMUR SMR-160 is a 160-MWe reactor being developed by Holtec International. The Holtec design targets elimination of as many active systems and components associated with the nuclear island as possible. Like NuScale, the SMR-160 relies on natural circulation and contains no reactor coolant pumps. The design also eliminates large diameter piping. Holtec characterizes the SMR-160 as an integral PWR. However, the design deviates from the standard definition of integral in that the steam generator and pressurizer are external to the reactor pressure vessel. These components represent a second "integral" unit that is directly joined to the RPV in an offset configuration with a single connection housing both hot and cold legs. Holtec reports key features of the SMR-160 to be: a substantially simplified, passive cooling system; simplified refueling through full core exchange as a single basket or cartridge; and passive cooling for the associated spent fuel pool.

Protection against severe accidents is provided through subsurface emplacement of the RPV and the presence of a large water inventory within an annular region of the upper containment for decay heat removal from the core and spent fuel pool. Adequate passive cooling is maintained via air cooling once the water inventory has evaporated.

For operation, the SMR-160 uses standard LWR fuel assemblies and offers simplified core design with the full core reloads. Use of soluble boron is eliminated, which simplifies coolant chemistry, maintenance, and related corrosion concerns. The SMR-160 can be deployed as a single stand-alone system.

3.3.4 Westinghouse Small Modular Reactor (W-SMR)[37]

The Westinghouse W-SMR is a 225-MWe integral PWR. The W-SMR represents more of an evolutionary design than other iPWRs in that it shares a greater number of features and attributes with current and new LWRs, including the Westinghouse AP1000. Accordingly, the W-SMR may be attractive for utilities seeking reduced risk with respect to licensing, construction and operations, albeit at the expense of more passive safety systems and overall design simplification.

Westinghouse's evolutionary approach to lwSMR design reflects a deliberate design philosophy seeking to maximize leveraging of current licensing, construction, operation and maintenance experience. Westinghouse is also able to take advantage of testing methods, component technologies and modular construction approaches developed for AP1000 deployment. Important

[36] T. Marcille. *Holtec International's SMR-160*. Nuclear News. December 2014. p. 73-76.

[37] K. Paserba. *The Westinghouse SMR: Simpler, smaller, and safer*. Nuclear News. December2014. P. 81-84.

similarities with current LWR technology include the use of standard 17 x 17 PWR fuel assembly, fuel cladding materials, and uranium enrichments (i.e., below 5%). The W-SMR also continues use of reactor coolant pumps (and AC power) for forced reactor coolant flow under normal operations. Refueling falls within the current industry envelope with 40% core replacement on 24-month cycles. Reactivity control during normal operation is achieved through the use of soluble boron; control rods are used for shutdown and coarser power adjustment (e.g., load following).

The W-SMR design offers defense in depth for passive decay heat removal via three diverse approaches: introduction of gravity fed cooling water from the steam generator, use of passive heat exchangers and use of bleed and feed methods. Plant safety systems do not require AC power and provide safe shutdown for seven days before additional makeup water is required. Batteries supply power for instrumentation and controls and operation of safety system and isolation valves. As with other lwSMRs, location of essential components below ground (e.g., the reactor core and control room) provides robust protection against external hazards and threats for enhanced safety and security.

The W-SMR is designed for transportation by all modes (rail, truck and barge), full modular construction, and a 24month schedule. The W-SMR is deployable as a single-unit plant.

3.4 Non-USD Small Modular Reactor Designs

Table 3-2 indicates that the majority of lwSMR designs offered in the global marketplace are of non-US origin. Among these, information is presented below on designs from Argentina's National Atomic Energy Commission (CNEA), the China National Nuclear Corporation (CNNC), the Korean Atomic Energy Research Institute (KAERI) and Russia's I.I. Afrikantov OKB Mechanical Engineering (OKBM Afrikantov).

3.4.1 CNNC ACP100[38]

China National Nuclear Corporation is developing the 100-MWe ACP100 SMR, emphasizing passive safety in a smaller LWR package. The RPV contains the core, reactor coolant pump, control rod drive mechanism, and steam generator. The location of the pressurizer outside of the RPV means the ACP100 is not classified as an integrated PWR. As with the Westinghouse W-SMR, the ACP100 represents a more evolutionary approach that incorporates many design and operational characteristics of GEN III/III+ LWRs. The ACP100 accommodates standard 17 x 17 PWR fuel assembly geometry and operates on 24-month cycles.

[38] D. Kovan. *Advanced SMRs: Providing new nuclear opportunities*. Nuclear News. December 2014. p. 85-87.

The ACP100 relies on an integrated pump (and AC power) for forced coolant circulation through the core. The ACP100 employs diverse, defense in depth safety approaches to ensure passive decay heat removal. Battery systems provide a 3-day supply of DC power for safety systems extendable with available recharging capabilities. Passive cooling provides 72-hour decay heat removal without operator intervention; passive cooling is extendable to 14 days with gravity-fed water addition.

The placement of reactor building and spent fuel pool underground provide additional protection against external threats and hazards for enhanced safety and security. Post-Fukushima design has also emphasized robust spent fuel pool design and cooling and flood protection.

Reporting indicates a serious effort to deploy prototype units in the near future; the design is progressing with a 2014 preliminary safety analysis report (PSAR) approval, presumably by the Chinese nuclear regulatory authority, and plans have been announced for construction of two units in Putian City, Fujian Province.

3.4.2 CNEA CAREM[39]

CNEA of Argentina is developing the Central Argentina de Elementos Modulares (CAREM) small modular iPWR with a net electrical capacity of 100 – 150 MWe. Construction on CAREM-25, a 25 MWe demonstration began in 2014 on a site adjacent to the Atucha nuclear plant near Buenos Aires, Argentina; completion is slated for 2018. The integral design incorporates 12 small helical once-through steam generators and hydraulic control rod mechanisms within the reactor pressure vessel. The CAREM design further simplifies the PWR design by eliminating the use of a pressurizer and primary coolant pumps by relying on "self-pressurization" for coolant pressure control and natural circulation for coolant flow. In addition to a pump driven conventional secondary loop for heat transfer during normal operations, passive heat removal provides a 36-hour grace period for station black out conditions. Construction and operation of CAREM-25 are intended to inform scale up and commercialization of larger units.

3.4.3 KAERI SMART[40]

The Korean Atomic Energy Research Institute (KAERI) is developing the System-integrated Modular Advanced ReacTor (SMART) as an integrated, 100 MWe PWR design. The SMART design uses coolant pumps (and therefore AC power) to provide forced coolant circulation through the core during normal operations. Passive cooling provides 36 hours of core protection through decay heat removal without operator action. The SMART reactor utilizes standard 17 x

---

[39] D. Kovan. *Advanced SMRs: Providing new nuclear opportunities*. Nuclear News. December 2014. p. 85-87.

[40] D. Kovan. *Advanced SMRs: Providing new nuclear opportunities*. Nuclear News. December 2014. p. 85-87.

17 PWR fuel assembly configurations; offers an extended batch reload cycle of 36 months; and provides simplified core design through a two-batch reload scheme.

The SMART design is reported to have received design approval in 2012 from the Korean nuclear regulatory authority, making it the first iPWR to receive design certification or approval. A domestic market for lwSMRs has not materialized in South Korea. However, Saudi Arabia has expressed interest in the SMART design and the two countries signed a memorandum of understanding in March 2015 to explore joint development and future commercialization in the Gulf region and elsewhere.[41]

3.4.4 OKBM Afrikantov KLT-40S[42]

The KLT-40S design is a small (35 MWe) PWR derived from commercial marine propulsion systems used in the Russian nuclear icebreaker fleet. The KLT-40S represents a scaled down version of current LWR technology and is not an integral design. The concept is designed for tandem unit deployment as floating power plants, conceivable to provide flexible deployment to suitable locations on barge accessible sites located on coasts and rivers. The KLT-40S is one of two designs actually being built. The first of a kind (FOAK) plant was licensed in 2003. Construction began in 2007, and completion is anticipated late 2016.

3.4.5 OKBM Afrikantov VBER-300[43]

The Russian vendor OKBM Afrkantov is also developing the VBER-300, which represents an evolution from the KLT-40S. The reference concept is a 4-loop, 295 MWe design; however, smaller 3-loop (230 MWe) and 2-loop (150 MWe) configurations are available. While the original concept was developed with deployment as barge-mounted twin unit plants in mind, the current concept extends to include land based applications as well. The design is reported to be in licensing.

3.4.6 SNERDI/SNPTC CAP-200[44]

The Shanghai Nuclear Engineering Research and Design Institute is also developing a line of small modular reactors in addition to the larger progeny from the nationalization of AP-1000 technology. CAP-200 is based on the experience of the PWR technology R&D, construction and safe operation. It is the outcome

---

[41] Early-stage pact signed for study of South Korea's SMART reactor. Nuclear News. April 2015. P. 48-49.

[42] D. Kovan. *Advanced SMRs: Providing new nuclear opportunities*. Nuclear News. December 2014. p. 85-87.

[43] Ux Consulting Company. *SMR Design Profile: VBER-300*. April 16, 2013.

[44] Advances in SMR Technology Developments, IAEA, https://aris.iaea.org/Publications/SMR-Book_2016.pdf

of accumulated experience with construction of the world's first batch of AP-1000 units and the R&D on CAP-1400 units. It also adopts an enhanced set of safety measures, based on the post-Fukushima lessons.

CAP-200 is a small PWR which is designed with improved safety, flexibility and environmental friendliness, and is also comparable with other SMRs on economy. It has a 2-loop compact layout primary system (main primary equipment including the RPV, SGs and reactor coolant pumps are connected by short pressure nozzles so that main pipelines are eliminated), it has modularized construction features, redundant and diversified passive safety features and a steel containment located below ground level.

3.5 Advanced Reactors

In the United States and Canada, a June 2015 report from Third Way lists 29 companies in North America who are vying for the future of nuclear with advanced fisson-based reactor technologies.[45] This number continues to grow, and the total number of global entities pursuing advanced reactor concepts currently exceeds fifty. As previously mentioned, advanced reactors are new designs (usually non-light water) that offer significant improvements with respect to current nuclear technologies),

3.5.1 Small Modular Generation IV Systems

A subset of these designs from a wide range of developers are summarized in Table 3-3 and in the text that follows. This list is intended to be illustrative and representative of the wide range of designs and capabilities offered as well as the relative maturity of the developer/vendor and designs, and new designs to emerge.[46]

[45] S. Brinton. *Introducing the Advanced Nuclear Industry*. Third Way. June 15, 2015. http://www.thirdway.org/report/the-advanced-nuclear-industry

[46] A major 2015 funding opportunity from the U.S. DOE to promote further development of two advanced reactor designs by industry-led teams has been accompanied by surprise announcements of new plans for reactor systems from Westinghouse (with a lead-cooled fast reactor) and TerraPower (with a chloride-based, liquid-fueled molten salt fast reactor).

Table 3-3
Representative Advanced Generation IV Reactors47,48

Company	Design	Country	Type	Core Outlet Temp. (°C)	Thermal output per module (MWth)	Electrical output per module or unit (MWe)	Under construction
AKME Engineering	SVBR-100	Russia	LFR	500	280	101	No
AREVA/ NGNP Alliance[a]	SC-HTGR	France/ United States	HTGR	750	625	272	No
Gen4 Energy[b]	G4M	United States	LFR	500	70	25	No
General Atomics	EM^2	United States	GFR	850	500	265	No
GE-Hitachi	PRISM	United States	SFR	485	840	311	No
Terrestrial Energy	IMSR	Canada and United States	MSR	700	80/300/600	32.5/141/291d[c]	No
Toshiba	4S	Japan	SFR	510	30 / 135	10 / 50[d]	No
Tsinghua & Huaneng	HTR-PM	China	HTGR	750	250 x 2	211	Yes (2)[e]
X-energy	Xe-100	United States	HTGR	750	125	45	No

[a] AREVA developed SC-HTGR based on its ANTARES core design; SC-HTGR selected by the Next Generation Nuclear Plant (NGNP) Alliance for commercialization it U.S.
[b] Formerly known as Hyperion Power Generation.
[c] Three power levels have been proposed for the IMSR.
[d] Two power outputs have been proposed for the 4S design; 30 and 135 MWth are presented here. (IAEA ARIS, Toshiba 4S, updated in 2013; https://aris.iaea.org/sites/..%5CPDF%5C4S.pdf).
[e] HTR-PM designed as tandem reactor modules coupled to a single turbine. The demonstration features one dual-module power unit. Construction of four more modules is imminent as a full-scale commercial prototype comprising two twin-modules per power block.

---

[47] *Nuclear Energy Technology Roadmap: 2015 Edition*. OECD/IEA and OECD/NEA. Paris. 2015.

[48] C. Vigoroso and J. Hinze. *The Great SMR Race*. Nuclear Engineering International. May 2013. http://www.neimagazine.com/features/featurethe-great-smr-race/

3.5.1.1 AREVA and Next Generation Nuclear Plant (NGNP) Alliance Steam Cycle High-Temperature Gas-Cooled Reactor (SC-HTGR)[49]

AREVA is developing a small modular HTGR primarily for supplying high quality industrial process heat; electricity generation represents a secondary product, e.g., as part of a cogeneration model. The core design is based on AREVA's prior work on the ANTARES HTGR concept. In this regard, AREVA incorporates the TRISO-based fuel in prismatic-blocks of graphite, as opposed to individual fuel pebbles. Unlike the ANTARES, the SC-HTGR design targets lower operating temperatures, allowing for use of more conventional materials and proven technologies such as low allow steels and a Rankine steam cycle. This leaves fuel and nuclear-grade graphite qualification as the major remaining issues requiring resolution, areas that are being addressed by ongoing R&D sponsored by the U.S. DOE.

Reactor control and shutdown under normal operations is accomplished through the insertion of conventional control rods. A second independent shut down method works by dropping neutron absorbing material into the core. For defense in depth, the inherent negative temperature feedback is deemed sufficient to shut the reactor down following a modest temperature rise. The SC-HTGR also invokes three independent heat removal approaches. First is the active use of two-loop primary circuit for normal operation. A second independent, dedicated active cooling system is provided for cooling the base of the RPV. A third provides passive cooling through natural convective flow similar to that used in other HTGR designs. And as with other HTGRs, the inherent high heat tolerance of the active fuel means that projected temperature excursions under severe accident scenarios (up to ~ 1300 °C) do not challenge fuel temperature limits. As with other lwSMRs, the SC-HTGR design can be configured to accept multiple (up to four) reactor modules per reactor and be incrementally deployed to suit customer financial needs, load growth and grid limitations.

3.5.1.2 Tsinghua & Huaneng High-Temperature Reactor – Pebble-Bed Module (HTR-PM)[50]

Tsinghua University is developing a pebble-bed helium-cooled HTGR design based on twin 100 MWe reactor modules coupled to a shared steam turbine. The fuel pebbles (6-cm in diameter spheres) comprise a graphite bulk matrix and dispersed TRISO fuel particles containing 8.5% enriched UO2. Circulation of the pebbles through the core and online refueling maximizes fuel utilization while reducing the need for excess reactivity. Average fuel residence time and burnup are reported to be 3 years and 90 GWd/MTHM. Fuel design is not considered favorable for reprocessing; therefore, this reactor is expected to

---

[49] J. Mayer and F. Shahrokhi. The Steam-Cycle High-Temperature Gas-Cooled Reactor. Nuclear News. December 2014. p.68-72.

[50] IAEA Advanced Reactor Information System. 2013. Status report 96 - High Temperature Gas Cooled Reactor - Pebble-Bed Module (HTR-PM). https://aris.iaea.org/PDF/HTR-PM.pdf

operate on a once-through fuel cycle. Control rods are used for normal operation reactivity control and for shutdown.

The helium coolant is circulated with the use of large blower fans. As with other HTGRs, the reactor core provides a large amount of heat capacity and negative feedback (reactivity coefficient) with increasing temperature. As a result, the system can tolerate a complete loss of coolant event without compromising the integrity of the fuel or the reactor system itself.

The HTR-PM program represents the culmination of a Chinese research project initiated in the 1970s, on high-temperature gas-cooled breeder reactors operating on a thorium fuel cycle, which shifted to thermal HTGR systems and included cooperation with the successful German program on pebble-bed designs. Chinese interest in HTGRs focused on use of high-quality nuclear heat for cogeneration applications as a means to displace industrial reliance on fossil fuel. In early 2000s, the HTR-10, a 10 MWth experimental pebble-bed HTGR reactor, was commissioned. The Chinese government has made maturation of the HTR-PM a top priority under its Chinese Science and Technology Plan. Construction a two-module demonstration unit is nearing completion and planning for commercial prototype four-module, two-power unit plant is underway. In parallel, a fuel fabrication plant is under construction based on technology licensed from Germany. As with the AREVA SC-HTGR design, development of the HTR-PM is targeting nearer term deployment by prioritizing use of mature, demonstrated technologies.

Unlike the stated objective for the AREVA design, baseload electricity generation is the primary mission for the HTR-PM. Targets for economic operation include a 90% availability factor, a Rankine power conversion system thermal efficiency of 40%, and economic competitiveness with LWR operation. The result appears to be a maturing HTGR technology that could be commercially available in the 2025 - 2030 timeframe.

3.5.1.3 AKME Engineering SVBR-100[51]

The Russian Federation industrial firm AKME Engineering is developing a 100 MWe integral small modular lead-bismuth eutectic (LBE) cooled fast reactor. Forced circulation of primary coolant is used during normal operation. Natural convection of LBE coolant is sufficient to provide adequate heat removal to avoid core damage if active cooling is lost. The integral design incorporates all primary system components within the reactor vessel, eliminating the need for piping, use of lead-bismuth compatible valves and enhancing passive safety features.

Reactivity control during normal operation is provided by control rod insertion. Emergency shutdown without operator intervention is enabled through the use of fusible links for emergency control rods, which drop into reactor once core

[51] IAEA. Advanced Reactor Information System. 2013. SVBR-100 (AKME Engineering, Russian Federation) https://aris.iaea.org/PDF/SVBR-100.pdf

temperatures reach the melting point of the links. Protection against overpressure is provided through use of membrane burst discs.

Startup fuel composition is 16.5% enriched UO2; transition to a closed fuel cycle with recycle of U and Pu would involve switching to mixed-oxide fuel. The primary mission for the SVBR-100 is electricity generation using a Rankine steam cycle. Recycling of U and Pu in a closed fuel cycle also offers the potential for significant increase in natural resource utilization.

3.5.1.4 GE-Hitachi Power Reactor Inherently Safe Module (PRISM)[52,53,54]

GE-Hitachi (GEH) continues to develop its PRISM SFR design. PRISM is reported to be in the "detailed design" stage, having benefitted from over 30 years of development beginning with work in the early 1980s under the U.S. DOE Advanced Liquid Metal Reactor program and extensive work on the Integral Fast Reactor concept derived from the successful long-term operation of the EBR-II reactor.

Due to this prolonged exposure, the PRISM design has received more regulatory scrutiny that other advanced non-light-water reactor concepts addressed in this report and should be considered among the more mature among the advanced reactor community. The USNRC published a pre-application safety evaluation report for an earlier PRISM incarnation in 1994.[55] Work continued through the 1990s and 2000s; with subsequent incorporation of modular design, the current evolution is formally designated as "Super" PRISM (S-PRISM). For simplicity, PRISM will be used interchangeably here for the latest version. GEH submitted a licensing strategy document to the USNRC in 2010.[56]

Each PRISM module is sized for 840 MWth and 311 MWe. A complete PRISM power block comprises two reactor modules with dedicated steam generators coupled to a single steam turbine-generator set for a total generation of 622 MWe. Commercial scale deployment is proposed for a total of three power blocks, comprising six reactor modules, three turbine-generator sets for a total electrical output of 1866 MWe. PRISM deployment also includes the potential for integration with onsite electrochemical processing of irradiated metallic fuel as part of the Advanced Recycling Center concept; this modular

---

[52] D.J. Powell. *PRISM: Redefining the relationship with plutonium*. Nuclear News. December 2014. P.64-66.

[53] World Nuclear Association. *Small Nuclear Power Reactors*. Updated 27 October 2014. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Small-Nuclear-Power-Reactors/

[54] IAEA. Advanced Reactor Information System. 2013. PRISM (GE-Hitachi, USA). https://aris.iaea.org/PDF/PRISM.pdf

[55] USNRC. 1994. *Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor.* NUREG-1368.

[56] GEH Submittal of Licensing Strategy Document for PRISM. 21 April 2010. Public version available from NRC as ML101230532. http://pbadupws.nrc.gov/docs/ML1012/ML101230532.pdf

approach allows for commercial-scale (rather than national-scale) deployment of a closed-fuel cycle nuclear energy system. The PRISM is a pool-type SFR, operating at 500 °C and employing forced circulation using electromagnetic pumps for its primary system. Core and fuel cycle design are based on U-Pu-Zr metallic fuel and are optimized for maximum fuel utilization and 18 – 24 month refueling cycles. Reactor control is provided via ten control and three shutdown assemblies. Favorable feedback behavior associated with the liquid sodium coolant and the fuel support inherent reactor safety in terms of stability, control and shutdown. For off-normal and accident conditions, GEH reports passive safety features that provide adequate cooling capacity indefinitely without operator intervention through the incorporation of a Reactor Vessel Auxiliary Cooling System (RVACS) and other features.

GEH is pursuing a customer for the FOAK plant and does not appear to be considering a pre-commercial demonstration as part of its path to commercialization. The primary mission and business case for PRISM is electricity generation; other potential missions derive from the capabilities offered by operation in a fast spectrum and include resource extension through recycling of existing and new inventories of used fuel (i.e., breeding) and actinide management (i.e., burning) to reduce inventories of long-lived and high heat load radioactive wastes sent to a geologic repository. The trade press reports ongoing discussions with the UK government and a strategic partnership with Spain's Iberdrola for deployment of PRISM to manage its large stockpile of separated plutonium arising from decades of Magnox fuel reprocessing.[57,58]

3.5.1.5 General Atomics Energy Multiplier Module (EM^2)[59,60,61,62,63]

General Atomics (GA) is developing a small modular 500 MWth helium-cooled gas fast reactor with flexible fuel use supporting burning of used LWR fuel.

The EM^2 represents a major evolution from prior GA thermal HTGR designs in terms of the fast spectrum, higher energy density, and higher temperatures, i.e., >

---

[57] World Nuclear News. 2011. *Prism proposed for UK plutonium disposal*. 1 December 2011. http://www.world-nuclear-news.org/WR-Prism_proposed_for_UK_plutonium_disposal-0112114.html

[58] World Nuclear News. 2014. *Iberdrola joins GE-Hitachi for Prism.* 23 July 2014. http://www.world-nuclear-news.org/NN-Iberdrola-joins-GE-Hitachi-for-Prism-2307141.html

[59] R. Schleicher and C.A. Back. *EM^2: A high-efficiency gas-cooled fast reactor*. Nuclear News. December 2014. P. 50-53.

[60] IAEA Advanced Reactor Information System. 2013. EM^2 (General Atomics, USA). https://aris.iaea.org/PDF/EM2.pdf

[61] J. Parmentola. 2015. *Advanced Reactors & Changing the Economic Paradigm*. Presentation to U.S. DOE Nuclear Energy Advisory Committee, Advanced Reactor Technology Subcommittee. January 2015.

[62] http://www.ga.com/energy-multiplier-module

[63] H. Choi, R. W. Schleicher, and P. Gupta. *A compact gas-cooled fast reactor with an ultra-long fuel cycle*. Science and Technology of Nuclear Installations. Volume 2013 (2013), Article ID 618707. http://dx.doi.org/10.1155/2013/618707

850 °C. GA frames its vision for a safe, cost competitive GFR in terms of the following design principles and constraints relative to the current LWR technology:

- Competitive cost-wise with fossil and other electricity generation through reduced size and increased thermal efficiency for electricity generation;
- Increased passive safety;
- Increased fuel utilization and flexibility with fast neutron spectrum, including the ability to recycle used nuclear fuel with minimal processing and no actinide separation;
- Operational flexibility and maneuverability (e.g., for load following);
- Increased siting flexibility (e.g., through use of dry cooling to minimize water requirements).

The operational envelope of EM^2 encompasses higher temperatures and radiation damage than many other concepts. Therefore, unlike development strategies favoring maturity and availability of materials and components for nearer term deployment, GA's approach to EM^2 commercialization requires further development and maturation of fuel, fuel processing, and material technologies.

High outlet temperatures offer substantial increases in thermal efficiency through the use of a combined Brayton and organic Rankine bottoming cycle. Thermal efficiencies of 53% for wet-cooling and 48% for dry-cooling configurations correspond to electrical outputs of 265 and 240 MWe per module, respectively. The proposed reference plant for EM^2 comprises four modules delivering a total of 1,060 MWe for wet-cooling and 960 MWe for dry-cooling. The anticipated plant footprint is anticipated to be 9 hectares. Modularity and scale should drive shorter, more predictable construction schedules, i.e., on the order of 42 months.

The reference EM^2 core concept comprises uranium carbide (UC) fuel plates clad in advanced, refractory SiC-SiC; fuel plates stack horizontally to form fuel assemblies. Twenty-one assemblies are arranged to form a core layer, and 17 stacked layers form the active core. The core is enveloped in beryllium oxide (BeO), graphite and boron carbide (B_4C) for neutron management (reflection and shielding). Cores are designed for 30-year lifetimes, with plant lifetimes on the order of 60-years. Fuel flexibility allows for use of either low-enriched uranium or uranium-plutonium mixed oxide (MOX) fuel and potential loading of used nuclear fuel from LWRs, depleted and natural uranium, or thorium as fertile support for breeding of new fissile fuel.

Used fuel would be processed via a dry, direct air oxidation process to avoid separation of actinides for proliferation resistance. Additional uranium enrichment is not required after startup of a first generation fleet; as the subsequent generations are fueled by the discharged core materials of the previous ones. The power conversion system for the EM^2 also represents the introduction of new and innovative technologies to achieve compactness and thermal efficiencies to support the desired economic business case. The primary power conversion system is one being developed by GA uniquely for EM^2 effort that offers a compact, integrated high-speed gas turbine with variable speed generator for responsiveness to load demand.

3.5.1.6 GEN4 Energy Inc. G4M[64]

GEN4 Energy, Inc., formerly Hyperion Power Generation Inc., is developing a small modular lead-bismuth-cooled fast reactor capable of delivering 70 MWth and 25 MWe. The design is derived from a Los Alamos National Laboratory concept. The reactor is fully modular and compatible with minimal human operational intervention for remote deployments as "nuclear battery" with a 10-year core life, no onsite refueling, and transportation as an intact reactor unit. Under normal operations, the primary coolant is circulated using powered pumps, while full passive safety available for any off normal occurrences and "walk-away safe" performance. GEN4 Energy won a U.S. DOE award to evaluate natural circulation capabilities for the lead-bismuth based advanced reactors.[65]

The G4M is being promoted as simplified, small scale nuclear generation option based on a robust safety case derived from inherent properties of the coolant, i.e., near ambient system pressure, high boiling temperature of the coolant, and benign coolant-material reactions.[66] The G4M is also amenable to production line manufacturing and truck based manufacturing as a result of its small size. The elimination of onsite access to and handling of fuel and other core components conceivably eliminates the need for many infrastructure and staff capabilities. Therefore, deployment to remote sites with minimal infrastructure and staffing requirements is a niche market that GEN4 and other developers offering nuclear battery concepts are targeting as a new nuclear opportunity not available with more traditional GWe scale plants.

Low-enriched (19/75%) uranium nitride in HT-9 cladding comprise the reference G4M fuel system. Radiation tolerant stainless steels, HT-9 and T-91, are the primary candidates for mature, available structural materials. A quartz radial reflector reduces neutron leakage. Standard B_4C control rods are used for reactivity control and shutdown for normal operations. Two additional, independent shutdown systems triggered without operator intervention are incorporated as well: a separate set of B_4C shutdown rods and a reserve shutdown system, which consists of dropping B_4C balls dropped into a central reactor core channel.

---

[64] http://www.gen4energy.com/applications/

[65] GEN4 Energy Press Release. GEN4 Energy Team Awarded Advanced Reactor R&D Grant. 12 November 2013. http://www.gen4energy.com/news_item/gen4-energy-team-awarded-advanced-reactor-rd-grant/

[66] Lead and lead-bismuth coolants do not present analogs to hazards in light-water and sodium-cooled systems, i.e., exothermic, hydrogen generating reactions of zirconium metal with oxygen and water under severe accident conditions (> 600 °C) and violent reactions of liquid metallic sodium with oxygen, respectively.

Gen4 Energy is targeting three niche markets and applications for its reactor: extractive industries (mining and oil/gas production), isolated/island communities, and government facilities.

3.5.1.7 Terrestrial Energy Integral Molten Salt Reactor (IMSR)[67]

Terrestrial Energy of Canada is developing a scalable variant of the liquid-fueled, graphite-moderated molten salt reactor optimized as a thermal burner (converter) reactor as opposed to breeding. Fuel use is flexible; the reactor can be started on low-enriched (<20%) ^{235}U fuel and sustained on the U-Pu or Th-^{233}U fuel cycles. This burner approach is derived from the Denatured Molten Salt Reactor (DMSR) concept developed at ORNL in the late 1970s era in which proliferation resistance was emphasized over breeding and reliance on reprocessing. The burner approach relaxes some important and challenging design constraints with respect to the need for onsite fuel salt processing and Li-based salts highly-enriched in Lithium-7 for neutron economy and avoidance of excessive tritium production. A reference fuel salt composition has not been identified in available design descriptions, although the use of salts other than Li-based ones is touted as an important feature.

Specific attributes of this design include limited life components contained in reactor core module, sealed, and designed for full cartridge replacement. Truck transportable, modular deployment in units of two independent reactor core enables the cartridge/battery model of refueling and maintenance. Only one of the two reactor cores per module operates at any time; when economic life is reached (currently 7-year life of core) or other issues require retirement, connection to balance of plant is transferred to the second core and the first (used) core module is shipped off-site for repair and recycling/refueling/reuse.

3.5.1.8 Toshiba Super Safe, Small and Simple (4S)[68]

Toshiba in cooperation with a research consortium led by the Central Research Institute of Electric Power Industry (CRIEPI) has developed the 4S design as a small, pool-type, sodium-cooled fast reactor offered at two power levels – 10 and 50 MWe. The size range and 30-year core life puts the 4S in the “nuclear battery’ category, making it appropriate for island and remote deployment. The city of Galena, Alaska, previously expressed significant interest in the use of the 4S for as a municipal power supply.

The reactor is an integral lwSMR; all primary components are installed inside the reactor vessel. Major primary components are the Intermediate Heat Exchanger (IHX), primary EM pumps, moveable reflectors which form a primary reactivity control system, the ultimate shutdown rod which is a back-up shutdown system,

---

[67] Simon Irish and David Leblanc, 2014. *The Integral Molten Salt Reactor*. Nuclear News. November 2014.

[68] *Super-Safe, Small and Simple Reactor (4S, Toshiba Design)*. IAEA Advanced Reactor Information System. 2013.

radial shielding assemblies, core support plate, coolant inlet modules and fuel subassemblies. The design includes use of metallic (U-Zr alloy) fuel comprising two core zones: inner zone enrichments of 19 and 18 w/o ^{235}U for 10 and 30 MWe, respectively, and outer core zone enrichments of 17 and 12 w/o ^{235}U for 10 and 30 MWe, respectively. The 4S is designed for high-conversion to support the 30-year core life but not breeding. The 4S is capable of supporting both electricity generation missions (including load following) and non-electric process heat applications (e.g., desalination) with the incorporation of an appropriate balance of plant. Cost-competitiveness is achieved with factory production of NOAK units, high availability factors (i.e., > 95%), and construction duration of a year or less.

Toshiba engaged the U.S. NRC in pre-application meetings starting in 2007; however licensing activities are currently inactive.

3.5.1.9 X-energy Xe-100[69]

X-energy is developing a small modular HTGR (125 MWth/45+ MWe). The Xe-100 uses uranium oxycarbide fuel, TRISO particle based containment, and pebble bed fuel concept for the robust safety case associated with the pebble bed Xe-100. The principal market for Xe-100 is electricity, which includes baseload and load following generation. The reference commercial deployment model includes four modules, which together provide approximately 190 MWe of capacity. X-energy also promotes the operational maneuverability of the design allowing for rapid ramping and capable of stable operation at low power (~25% of peak) for extended periods. Combined heat and power is also offered as an optional business case for product flexibility. The company is also targeting an emergency planning zone (EPZ) with a radius of ~400m, less than the anticipated site boundary. The potential compatibility of the Xe-100 design with collocated industrial end users for heat and power was specifically called out in the 2014 DOE Technical Review Panel report.[70]

Established in 2010, the company has the backing of Stinger Ghaffarian Technologies, Inc. (SGT), an established government contractor providing systems engineering, logistical support, and information technology services to the aerospace sector, include the National Aeronautical and Space Administration (NASA).

X-energy has accelerated its entry into the GEN IV R&D arena by leveraging expertise and experience from South Africa's Pebble Bed Modular Reactor (PBMR) program in South Africa, the former leading program HTGR

[69] E. Mulder. 2015. X-energy presentation to NRC-DOE workshop on advanced non-LWRs. 1 September 2015. Available at: http://pbadupws.nrc.gov/docs/ML1524/ML15247A020.pdf

[70] DOE 2014. *Advanced reactor concepts Technical Review Panel public report*. U.S. Department of Energy. Washington, D.C. October 2014. http://www.energy.gov/sites/prod/files/2014/12/f19/Advance%20Reactor%20Concepts%20Technical%20Review%20Panel%20Public%20Report.pdf

development until being abandoned at an advanced stage in 2010.[71] The X-energy timeline assumes an active customer engaged immediately and targets a combined construction and operation license (COL) application submitted to the USNRC in 2017, Design Certification in 2024, and construction and deployment of the FOAK at the customer's site by 2030.

3.5.2 Other Notable Advanced Reactor Designs

Many other GEN IV designs are being proposed that produce thermal and electrical outputs above the operational 300 MWe SMR cutoff; these fall outside the focus of this update and are not be described in detail. Two frequently cited developers/designs (TerraPower Traveling Wave Reactor and Transatomic Power Reactor) are included here for reference.

3.5.2.1 TerraPower Traveling Wave Reactor (TWR)

TerraPower is developing a 600 MWe sodium cooled fast reactor variant to demonstrate deep burning of in core fissile and fertile inventories - the Traveling Wave Reactor (TWR). Using this approach, the TWR eschews removal and reprocessing of fuel in favor of maximizing in situ fuel utilization. TerraPower is an offspring of venture capital firm, Intellectual Ventures and enjoys high profile leadership and financial backing from the likes of Bill Gates and Nathan Myhrvold, Microsoft founder and former chief technology officer, respectively. The availability of substantial financial resources, significant staffing levels and evidence of substantial R&D activities indicate TerraPower represents a credible commercial venture. Notable R&D work includes extensive in-pile material testing at the BOR-60 fast reactor in Russia and fuel fabrication and testing.[72] TerraPower is targeting construction of the 600 MWe prototype by the early 2020s[73] and plans to scale up to a larger 1000 MWe commercial unit (which will use the principle of the Traveling Wave concept) soon after.

TerraPower has developed an extensive collaborative network to support TWR development; Babcock & Wilcox agreed to support TWR development in 2014, and TerraPower signed a memorandum of understanding with CNNC as a possible step toward demonstration and commercialization.[74] Media reporting indicates construction of prototypes outside of the U.S. is part of the demonstration phase strategy to avoid barriers and delays anticipated with the licensing and construction of first-of-a-kind units in the United States.

---

[71] World Nuclear News. *Government drops final curtain on PBMR*. 20 September 2010. http://www.world-nuclear-news.org/C-Government_drops_final_curtain_on_PBMR-2009108.html

[72] AREVA Press Release: AREVA Inc. completes fuel testing services for TerraPower. 2 February 2015.

[73] TWR-P ARIS Database, International Atomic Energy Agency, https://aris.iaea.org/sites/..%5CPDF%5CTWR-P.pdf

[74] World Nuclear News. *TerraPower, CNNC team up on travelling wave reactor*. 25 September 2015. http://www.world-nuclear-news.org/NN-TerraPower-CNNC-team-up-on-travelling-wave-reactor-25091501.html

3.5.2.2 TerraPower Molten Chloride Fast Reactor (MCFR)

TerraPower is also developing a gigawatt-class molten salt reactor, in additional to the already mentioned TWR design. Rather than using solid fuel, the MCFR uses liquid fuel composed of chloride salts, with strong negative temperature and void coefficients.[75] The fuel is dissolved in the coolant and flows through the core and the primary heat exchangers. This advanced reactor design exhibits inherently safe features, is reported to offer proliferation resistance (actinides stay in the core and are always mixed with lanthanides) and minimizes costs (no fuel fabrication needed, online refueling).

Expected high core outlet temperatures translate into substantial increases in thermal efficiency (for electricity production) while offering other product flexibility options (e.g. high quality heat generation and hydrogen production).

3.5.2.3 Transatomic Power (TAP) Reactor[76]

Transatomic Power is developing a 1250 MWth (550 MWe) variant of the liquid-fueled molten salt reactor. The TAP reactor has a thermal/epithermal neutron spectrum and has been designed specifically for operation on used nuclear fuel as its primary fuel feedstock, although operation on uranium with low enrichment levels (as low as 1.2%) is also possible. The reactor achieves actinide burnup up to 5 times that of a conventional LWR and can reduce annual long-lived waste production by over 80%. The TAP reactor uses lithium fluoride as the fuel salt, which can hold about 27 times as much uranium; as with other MSRs that incorporate lithium-based salts, lithium depleted in lithium-6 is required to avoid excessive tritium production and parasitic neutron absorption. The TAP design departs from other MSR variants by incorporating zirconium hydride as the moderator for a more compact design and higher fast neutron flux for actinide burning versus the standard use of graphite.

The company has received some private venture capital backing for startup and has outlined an aggressive development and business strategies and reports completing of the pre-conceptual design required for developing confirmatory testing plans, estimating reactor capital cost, and to prepare for final design development. Transatomic is aspiring to a commercial technology that competes favorably with coal on price and natural gas ($4 per million Btu) for electricity generation, offers a $2 billion overnight cost, and is ready for commercial prototype construction in 2020s. As with other developers targeting rapid commercialization, Transatomic has selected existing materials (modified Hastelloy N was initially proposed as the primary corrosion-resistant structural material, but it looks like it will be replaced by high-temperature ceramics, such

---

75 TerraPower and the Molten Chloride Fast Reactor, https://public.ornl.gov/conferences/MSR2015/pdf/16-151015%20-%20MCFR%20at%20TerraPowerJeffLatkowski.pdf

76 http://www.transatomicpower.com/the-science/

as SiC-SiC fiber composites)[77], a conventional steam cycle, and a lower operating temperature (650 ˚C), which could alleviate some of the technology risks associated with other molten salt reactor designs that aim for higher temperatures and advanced power conversion (i.e., those employing supercritical CO2 Brayton cycle technology).

3.6 Key National Gen IV R&D Programs

3.6.1 China

China has three of six Generation IV (GEN IV) advanced reactor designs either in operation, under construction, or being actively pursued. China is operating a grid-connected sodium fast reactor (SFR). The 65 MWth China Experimental Fast Reactor (CEFR) was constructed at the China Institute of Atomic Energy (CIEA), near Beijing, in cooperation with Russia, including the supply of major equipment and fuel by Russian firms.[78] CEFR became operational in 2010 and was connected to the grid in 2011. Initial plans called for scale-up the CEFR prototype to the 600 – 1000 MWe range under the Chinese Demonstration Fast Reactor (CDFR) Project 1, with construction beginning in 2017 and operation in 2023.

China is also operating a 10 MWth high-temperature gas-cooled experimental reactor, the HTR-10, utilizing pebble fuel. The HTR-10 represents China's entrance into the high-temperature nuclear technology arena. The reactor coolant outlet temperatures of 700 – 950 ˚C put it in the range for petrochemical refining and hydrogen production.

Following the HTR-10, construction is underway at the Shidaowan site in Shandong of two small modular helium-cooled high-temperature gas reactors (HTR-PM) employing pebble bed fuel. The two HTR-PM units will power a single 210 MWe turbine.[79] Construction began in 2012 and operation is expected in 2017.

China is also emerging as a leader in the development of molten salt reactor (MSR) technology, pioneered by Oak Ridge National Lab in the 1950s and 60s. China is pursuing both variants of the MSR: the original liquid-fueled design and the more evolutionary solid-fueled MSR. Plans for China's Thorium Molten Salt Reactor Nuclear Energy System (TMSR) R&D include construction and operation of two reactors and supporting infrastructure for the demonstration of

---

[77] Transatomic Power Corporation. Technical White Paper, v 2.0.0. July 2016.

[78] World Nuclear News. *Chinese fast reactor nears commissioning*. 7 April 2009. < http://www.world-nuclear-news.org/NN-Chinese_fast_reactor_nears_commissioning-0704095.html >

[79] World Nuclear New. *Helium fan produced for Chinese HTR-PM*. 19 August 2014. < http://www.world-nuclear-news.org/NN-Helium-fan-produced-for-Chinese-HTR-PM-1908144.html >

liquid- and solid-fueled molten salt reactor designs at test and pilot scales, in order to deploy advanced reactors commercially by 2030:[80]

- 10 MW solid-fueled MSR and a 2 MW liquid-fueled MSR by 2020.

3.6.2 France

The French nuclear energy strategy has targeted closure of the nuclear fuel cycle to support energy security and independence. Accordingly, research, development and demonstration for the purpose of commercial deployment of fast reactors have been central to the French investment in R&D and the development and operation of its nuclear infrastructure. To this end, successful operation of the experimental Phenix SFR led to the ambitious development and construction of the commercial scale (1200 MWe) Super Phenix SFR, which experienced reliability issues (8% availability) during its operational lifetime and was shutdown prematurely.

Development of a commercially viable fast reactor remains a priority for the French nuclear R&D program. The following GEN IV reactor programs are being pursued by French government and commercial entities independently or in partnership with European Union sponsored programs:

- ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) – 600 MWe prototype sodium-cooled fast reactor optimized for self-sustaining operation (i.e., low breeding ratios), high fuel burnup, and actinide destruction. ASTRID is intended to provide the technical basis for larger commercial versions (~1500 MWe) to be deployed in the 2050 timeframe.
- Allegro – 50 – 100 MWth experimental gas-cooled fast reactor (GFR) represents a parallel, albeit lower priority, track for fast reactor development co-sponsored by France.
- ANTARES – 625 MWth modular very high temperature gas-cooled reactor (VHTR) is being developed separately by AREVA as its commercial entry into the high temperature market with both near-term (electricity generation) and long-term (industrial process heat supply) applications.[81] The reactor design uses prismatic (as opposed to pebble bed) fuel and a conventional steam cycle for initial deployment.

3.6.3 India

The Prototype Fast Breeder Reactor (PFBR) is currently nearing completion in Kalpakkam, India.[82] PFBR construction began in October 2004 and project

---

[80] MIT Technology Review, *China Details Next-Gen Nuclear Reactor Program*. October 2015. https://www.technologyreview.com/s/542526/china-details-next-gen-nuclear-reactor-program/

[81] AREVA, Inc. *Information Kit: AREVA HTGR High Temperature Gas-cooled Reactor*. March 2014 < http://us.areva.com/home/liblocal/docs/nuclear/htgr/htgr-infokit-2014-03.pdf >

[82] World Nuclear Association. *Nuclear Power in India*. 30 July 2014. < http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/India/ >

completion has been delayed by approximately 4 years. Startup is expected in late 2016 or early 2017. Unlike most countries, India's long-range nuclear energy R&D program is focused on the strategic objective of achieving greater self-sufficiency in electricity generation by transitioning to a thorium-based nuclear fuel using largely indigenous reactor and fuel cycle technologies. Accordingly, India is the world leader in thorium processing R&D and technology, as well as in heavy water and fast reactor technologies.

Nearer term, planned reactor construction to support execution of India's thorium fuel cycle strategy is reported to include:

- Six additional 500 MWe fast reactors based on the PFBR design, with completion of four targeted for 2020.
- Construction of the first Advanced Heavy Water Reactor in the 2016-2017 timeframe for operation in 2022.

3.6.4 Japan

In the latest revision of its Basic Energy Plan, Japan reaffirmed its support for nuclear energy going forward to support clean energy goals and commitments, including restart of reactors after undergoing and passing new safety reviews and continued R&D on fast reactors.[83] Japan has been a leader in R&D and demonstration of fast reactor technology, although its newest prototype Monju, a 280 MWe loop design, (vs. pool type SFR) has suffered from reliability problems and operational mishaps.[84] Post-Fukushima, the future of Monju (and arguably other GEN IV reactor programs) was linked in 2012 to the direction of Japan's fuel cycle policy: termination if a shift to direct disposal of used fuel occurs and continued operation if closure of the nuclear fuel cycle remains the country's goal.

While the ultimate role for GEN IV systems in Japan's energy future remains uncertain, prior goals for a fast breeder program remain in place: operation of a 500 – 750 MWe demonstration fast breeder reactor by 2025 and commercial deployment of large (~ 1500 MWe) fast breeder reactors by 2050, i.e., the Japan Standard Fast Reactor (JSFR).

Japan's national energy plan also includes high-temperature reactor R&D. Since 1998, Japan has operated the 30 MWth High Temperature Engineering Test Reactor (HTTR) with a typical outlet temperature of 850 ˚C, although testing has confirmed operation at 950 ˚C. Further development of VHTR technology awaits further direction in terms of domestic applications, while arrangements are in place for collaboration on VHTR technology development in other countries (e.g., Kazakhstan, UAE, and Indonesia).

---

[83] World Nuclear News. *Japan retains nuclear in energy mix*. 11 April 2014. < http://www.world-nuclear-news.org/NP-Japan-retains-nuclear-in-energy-mix-1104147.html >

[84] World Nuclear Assocation. Nuclear Power in Japan. September 2014. <http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Japan/ >

3.6.5 Russia

Russia can be considered the world leader in demonstration and deployment of the sodium-cooled fast reactor, including exports.[85] Russia's 600 MWe demonstration reactor, the BN-600 (Beloyarsk 3), has been in operation and generating electricity since 1980 with an average load factor of 74% – within striking distance of a commercially viable facility.[86]

The BN-800 represents the next and final step in the apparent path to commercialization of the technology. Construction of the first BN-800 (Beloyarsk 4) began in 2006; funding shortfalls delayed startup until June 2014. Commercial operation began in December 2015. Two BN-800s are also slated for construction in China as an integral element in that country's path to commercial-scale SFR deployment.

The Russian path to industrial-scale deployment of the SFR domestically includes a larger 1200 MWe SFR design – the BN-1200. Construction could begin as soon as 2015, with commercial operation in 2020. Large scale deployment in Russia is reported to include plans for eight additional BN-1200s under construction and in operation by 2030.

3.6.6 South Korea (Republic of Korea)

South Korean interest in advanced (GEN IV) reactor development for commercial deployment is heavily focused on SFRs and the utilization of metallic nuclear fuel and pyroprocessing technologies.[87] Current Korean plans focus on development of the prototype Generation IV sodium-cooled fast reactor (PGSFR), a 400 MWth (150 MWe) prototype reactor slated for construction in 2022 and operation in 2028. A primary object for PGSFR will be the demonstration of metallic Low Enriched Fuel (LEU) – Zr based fuel as well as advanced transmutation fuel incorporating recycled transuranics for waste management missions. PGSFR appears to be the successor to earlier 150 and 600 MWth SFR designs, the Korea Advanced Liquid Metal Reactor (KALIMER), which date back to the early 1990s. The Korean roadmap for its SFR program calls for commercial deployment of a PGSFR-derived SFR by 2050.[88]

South Korea is also working on a lead-bismuth cooled fast reactor (LFR) design, with deployment in a small transportable modular format targeting a nuclear battery application featuring 20-year operation and return-to-supplier refueling.

---

[85] World Nuclear Association. *Nuclear Power in Russia*. September 2014. < http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/Russia--Nuclear-Power/ >

[86] International Atomic Energy Agency. *Nuclear Power Reactors in the World: 2013 Edition*. Reference Data Series No. 2. Vienna, 2013.

[87] World Nuclear Association. Nuclear Power in South Korea. September 2014. < http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/South-Korea/ >

[88] Sodium-cooled Fast Reactor development. KAERI, Sodium-cooled Fast Reactor development Agency, Daejeon, Korea.

As with other countries, a 300 MWth high-temperature reactor (VHTR) design geared toward hydrogen generation (950 °C outlet temperature) has also been proposed. Reported timelines include a 2016 construction start and 2020 operation.

3.6.7 United States

The U.S government investment has pulled back from pilot and demonstration to a "wait and see" posture. DOE is mainly sponsoring early R&D on advanced nuclear fuels (notably metallic transmutation fuels for fast reactors) and advanced separations processes. The Next Generation Nuclear Plant (NGNP) program was established by the 2005 Energy Policy Act, and envisioned commercial demonstration of an advanced reactor through a public-private partnership between the U.S. DOE and an industry consortium. The high-temperature gas-cooled reactor was chosen as the candidate technology, due in large part to the desirability of high-temperature outlet temperatures that could provide additional industrial applications, including high-temperature heat for petrochemical refining, hydrogen production, and other non-electricity products as part of a flexible, adaptable, and robust business model for new nuclear assets. Progress on NGNP has stalled due in part to a failure to get industry agreement on a cost-sharing arrangement. In contrast to other national programs, the U.S. advanced reactor landscape is characterized by private sector efforts to commercialize Generation IV concepts.

November 2015 has seen DOE review its program and issue a new roadmap and rollout a new initiative, the Gateway for Acceleration of Innovation in Nuclear (GAIN)[89] to facilitate developer access to U.S. national laboratory expertise and capabilities. As part of the GAIN initiative, DOE also announced in Summer of 2016 an additional investment of 82 million USD in Advanced Nuclear Technologies[90]. This investment is in addition to the selection of Southern Company (partnering with TerraPower, EPRI, Vanderbilt University and Oak Ridge National Lab) and X-Energy (partnering with BWXT, Oregon State University, Teledyne-Brown Engineering, Idaho National Lab and Oak Ridge National Lab) as part of a cost-share multi-year program, aimed to further develop and address key technical challenges to the design, construction and operation of advanced nuclear reactors[91]. The Southern Company-led team will perform integrated effects tests and materials suitability studies to support development of the Molten Chloride Fast Reactor (TerraPower MCFR design), while the X-energy-led team will work on the design and fuel development challenges of the Xe-100 Pebble Bed Advanced Reactor.

---

[89] DOE GAIN Initiative announcement. November 2015. https://www.whitehouse.gov/the-press-office/2015/11/06/fact-sheet-obama-administration-announces-actions-ensure-nuclear-energy

[90] Energy Department Invests $82 Million to Advanced Nuclear Technology. June 2016. http://energy.gov/technologytransitions/articles/energy-department-invests-82-million-advanced-nuclear-technology

[91] Energy Department Announces New Investments in Advanced Nuclear Power Reactors. January 2016. http://www.energy-department-announces-new-investments-advanced-nuclear-power-reactors-help-meet

Section 4: Economics of Nuclear Reactors

Of the numerous cost metrics available for informing investment decision-making, overnight capital cost and levelized cost of electricity (LCOE) represent two of the most commonly cited and available figures for lwSMRs and advanced reactors among what it a limited data set and are therefore used in cost competitiveness discussion below.

Overnight capital cost represents the core cost of a construction project without consideration of duration and associated financing costs (including interest) and is typically reported in units of USD per generating capacity (kW). Capital costs provided by developers and vendors generally do not include site specific costs such as land acquisition and site preparation, which are considered separately as owner's costs.

LCOE is defined as the cost in real dollars (net present value) of building, operating, and maintaining a generating plant for an assumed timeframe and duty. LCOE is expressed in units of USD per MWh. LCOE is a popular metric for comparing the cost competitiveness of different electricity generating technologies. LCOE can also represent the average cost of electricity at which a generating unit would break-even over its total life. Calculation of the LCOE include costs associated with capital, fuel, O&M, and financing. Treatment of decommissioning and waste disposal for nuclear varies by country.

4.1 Economics of Large LWR Plants

The historical trend toward large gigawatt-class reactors was motivated by the pursuit of economies of scale to realize overall lower capital investment required per unit capacity installed and power delivered. However, as capital costs for large nuclear construction projects now approaches or exceeds the total market value of many utilities seeking to build new generation and the risk appetite for private investors (on the order of 10 billion USD), developers of small modular LWRs and advanced reactors argue for a different economic model, i.e., that of the economy of unit construction.

For context, Table 4-1 provides illustrative overnight costs and LCOE for GWe-scale LWR electricity generation for a small subset of countries. What is immediately evident is the large range of capital costs and LCOE by country, with capital and electricity costs for nuclear generation in South Korea and China coming in less than half those for Hungary, United Kingdom and the United States. While these numbers are subject to a great deal of variation and uncertainty, the ranges do serve to define the competitive environment in which lwSMRs and advanced reactors will be evaluated. For a market like South Korea, the low cost of large nuclear suggests a challenging lwSMR business case, which has been confirmed in reality with the lack of a domestic market in South Korea for the SMART SMR. One conclusion to be drawn from these data is that the large variance in nuclear cost estimates makes economic competitiveness a site-, market- and country-specific evaluation.

Table 4-1
Overnight costs and levelized cost of electricity for GWe-class LWRs.[92,93]

Region	Country	Overnight Capital Cost (USD/KWe)	Levelized cost of electricity vs. different discount rates (USD/MWh)		
			3%	7%	10%
OECD	South Korea	2021	29.6	40.4	51.4
	Hungary	6215	53.9	89.9	125.0
	United Kingdom	5560 – 6920[a,94]	64.4	100.8	135.7
	United States	5330[b,95]	54.3	77.7	101.8
Non-OECD	China (two examples)	1807	26	37	49
		2615	31	48	64

[a] UK overnight cost estimates converted from pounds using 2013 average exchange rate of 0.665 £/USD.
[b] U.S. overnight cost estimates in 2012 USD from 2013 USEIA report for a two-unit 2234 MWe plant.

[92] *Cost of Generating Electricity: Executive Summary. 2015 Edition*. OECD/IEA and OECD/NEA. Paris. 2015. https://www.iea.org/Textbase/npsum/ElecCost2015SUM.pdf

[93] *The Economics of Nuclear Power*. World Nuclear Association. Updated September 2015. http://www.world-nuclear.org/info/economic-aspects/economics-of-nuclear-power/

[94] *Electricity Generation Costs*. UK Department of Energy and Climate Change. December 2013.

[95] *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants*. U.S. Energy Information Agency. Washington, D.C. April 2013.

4.2 Economics of lwSMRs and Advanced Reactors

lwSMRs and scalable advanced reactors share many of the same economic attributes based on similar arguments for the benefits of smaller scales, modular construction and flexible deployment. For lwSMRs and comparably-sized advanced reactors, the customer is trading economy of scale for economy of production, which can include the following attributes:[96]

- Smaller unit cost per reactor facilitating financing.
- Smaller unit thermal and electrical output allowing for greater compatibility with transmission infrastructure and non-electricity product demand.
- Multi-unit deployment offers economic path to redundancy of generation capacity (i.e., smaller net impact of one unit going offline).
- Modular construction offers the benefits of factory construction and transportation.
- Smaller scales and potential for intact removal of reactor and primary system offers potential reduction in decommissioning costs.
- Smaller scales and flexible deployment offers potential access to new markets including local power generation for remote and island applications and non-electric products such as district and process heat and desalination.

[96] *Current Status, Technical Feasibility and Economics of Small Nuclear Reactors*. OECD/NEA. Paris. June 2011.

Table 4-2
Estimated overnight and electricity costs for SMR and advanced reactor designs.

Developer	Design	Standard Plant Configuration	Total Plant Capacity (MWe)	Overnight Cost (USD/kWe)	LCOE[97] (USD/MWh)
BWXT	mPower	2 module plant	180	5000	90 - 100
Holtec	SMR-160	Single or multi-module plant	160	5000	–
NuScale	NuScale	12 module plant	600	5100	90 - 100
		UAMPS 12 module project estimate	600	5000	
Westinghouse[98]	SMR	Single or multi-module plant	225	≤ GWe LWRs	71 - 84[99]
KAERI[100]	SMART	Single or multi- module plant	100	5000[b]	–
AKME Engineering[101]	SVBR-100	Single or multi-module plant	100	4000 - 4500	60 – 70

---

97 LCOE ranges are derived from multiple public sources, mainly developer presentations at meetings and conferences sponsored by professional society, trade and international organizations.

98 K. Paserba. *The Westinghouse SMR: Simpler, smaller, and safer*. Nuclear News. December2014. P. 81-84.

99 A. Palin. *Small Modular Reactor Design and Application*. Westinghouse Electric Corporation. February 2013.

100 Nuclear Power in South Korea. World Nuclear Association. Updated October 2015. http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/South-Korea/

101 A. Kudryavtseva. *Fast reactors as a solution for future small-scale nuclear energy*. Presentation to IAEA International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13). Paris. March 3 – 7, 2013. https://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-03-04-03-07-CF-NPTD/T8.2/T8.2.kudryavtseva.pdf

Table 4-2 (continued)
Estimated overnight and electricity costs for SMR and advanced reactor designs.

Developer	Design	Standard Plant Configuration	Total Plant Capacity (MWe)	Overnight Cost (USD/kWe)	LCOE (USD/MWh)
Tsinghua & Huaneng[102]	HTR-PM	Deployment in twin module power blocks	211	1500	50
General Atomics[103]	EM^2	4 module plant	1060	4500 +970 (first 30-yr core)	~50% of large LWRs[c]
X-energy	Xe-100	4 module plant	190	5300	–
Toshiba[104]	4S	Single or multi-module plant	10/50	2500	50 - 70

[a] Includes operations, maintenance, fuel and decommissioning costs.
[b] Memorandum of understanding signed between South Korean and Saudi Arabia to evaluate feasibility of SMART commercialization in Middle East region.
[c] EM^2 developer General Atomics has established an aggressive economic target for electricity generation - a 50% LCOE of GWe LWRs due to a 850 °C operation by using a Brayton-cycle.

102 *Status report 96 – High Temperature Gas Cooled Reactor – Pebble-Bed Module (HTR-PM)*. IAEA Advanced Reactor Information System. 2013.

103 J. Parmentola. 2015. *Advanced Reactors & Changing the Economic Paradigm*. Presentation to U.S. DOE Nuclear Energy Advisory Committee, Advanced Reactor Technology Subcommittee. January 2015.

104 *Super-Safe, Small and Simple Reactor (4S, Toshiba Design)*. IAEA Advanced Reactor Information System. 2013.

A 2011 OECD/NEA review concludes that lwSMRs (and by extension advanced reactors) are unlikely to be competitive with large nuclear plants on an electricity cost basis alone, but does foresee situations where lwSMRs could be competitive with other generation technologies where large nuclear plants would not be feasible such as replacement for smaller retiring coal units (or for applications not suited for LWR technology).[105]

A review of publicly available information for overnight capital costs and LCOE for lwSMR and advanced reactor designs reveals telling trends among lwSMR and advanced reactor concepts. Overnight costs for both lwSMRs and advanced reactors generally converged on a 4000 - 5000 USD/KWe range. However, there are outliers with substantially lower capital costs, i.e., on the order of 2000 USD/KWe. In terms of LCOE, most lwSMR designs converged on LCOE estimates in the 90 - 100 USD/MWh. Advanced reactor developers generally report substantially lower LCOEs - on the order of 50 – 70 USD/MWh. Such estimates may be more aspirational than realistic and therefore require more information and further evaluation.

Many factors beyond just capital cost and LCOE, such as construction duration, cost of money, and O&M costs, influence the attractiveness of lwSMRs and advanced reactors to owner/operators and investors. The limited data available pertaining to lwSMR and advanced reactor economics calls for further review and analysis as new information comes to light.

4.3 Estimated Costs for Advanced Reactor Demonstrations and Prototypes

For most advanced reactors, one or more demonstration and/or prototype reactors will likely be needed to demonstrate function of the system and elements of economic feasibility. Very little information is available on cost for these systems. A 2010 Deloitte study evaluates funding mechanisms to support the European Union's European Sustainable Nuclear Industrial Initiative (ESNII) under the European Strategic Energy Technology Plan (SET-Plan) for the maturation of fast reactor technology options.[106] Table 4-3 summarizes the ranges of estimated funding requirements (in 2010 EUR) to complete the proposed demonstration/prototype reactors and associated fuel fabrication facilities.

---

[105] *Current Status, Technical Feasibility and Economics of Small Nuclear Reactors*. OECD/NEA. Paris. June 2011.

[106] Funding opportunities and legal status options for the future European Sustainable Nuclear Fission Industrial Initiative of the Strategic Energy Technology Plan. Deloitte. February 2010.

Table 4-3
Estimated Funding Required for Demonstration/Prototype Reactors.

Project	Technology	Planned Grid Connection?	Thermal or Electrical Output	Estimated Cost (billions of EUR)
ASTRID	SFR prototype	Yes	250 – 600 MWe	2 – 4
LEADER	LFR demonstration	Yes	100 MWe	0.8 - 1
European Technology Pilot Plant (ETPP)	LFR prototype	No	100 MWth	0.8
ALLEGRO	GFR demonstration	No	50 – 100 MWth	0.6 – 0.8
MOX fuel fabrication facility		0.6		
Advanced fuel fabrication facility		0.3 – 0.5		
Total		6 – 10		

4.4 Sitting Requirements

Deployment of lwSMRs and advanced nuclear systems will require compatibility with typical siting constraints and conditions. However, to the credit of small modular systems, these requirements and conditions should prove to be less restrictive and limiting (particularly if the small modular concept is to compete with larger nuclear units and other generation sources).[107] From a licensing perspective, the principal siting criteria include consideration of and compatibility with:[108]

- Geology and seismology
- Atmospheric extremes and dispersion
- Exclusion area and low population zone
- Population considerations
- Emergency planning
- Security plans
- Hydrology
  - flooding
  - water availability
  - water quality
- Industrial, military, and transportation facilities
- Ecological systems and biota
- Land use and aesthetics
- Socioeconomics
- Noise limits

In addition to these regulatory considerations, commercial viability of a new plant includes access to adequate:

- Transportation infrastructure;
- Transmission and distribution infrastructure for electricity and non-electric products.

For brown field construction where new nuclear generation is replacing existing fossil generation, deployment of lwSMRs and smaller advanced reactors will require compatibility with the limitations and constraints imposed by the existing grid connections and available land area. In terms of replacement generation

[107] Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Power Generation Facilities (Siting Guide), Revision 0. EPRI, Palo Alto, CA. June 2015. 3002005435

[108] USNRC. 1998. Regulatory Guide 4.7 - General Site Suitability Criteria for Nuclear Power Stations. Revision 2.

capacity, an ORNL SMR siting study identified 2000 coal-fired units in the United States at 800 plant sites. Of these, 148 coal plant sites fell within ORNL screening criteria for replacement by SMRs in terms of capacity (i.e., greater than 50 MWe and less than 540 MWe) and age (i.e., pre-1980 vintage). Detailed analysis of a 34 plant subset indicated that 77% appeared to be suitable candidates for SMR deployment.[109]

For green field deployment, ORNL evaluated U.S. based on four primary criteria: site expandability, economics and proximity to demand, acceptability, and engineering. Locations meeting all four of these are shaded in green, with gradations meant to reflect further differentiation among sites from "good" to "best". The report noted that the "best" category corresponds to approximately 20% of the contiguous U.S. land area illustrated in Figure 4-1 below.

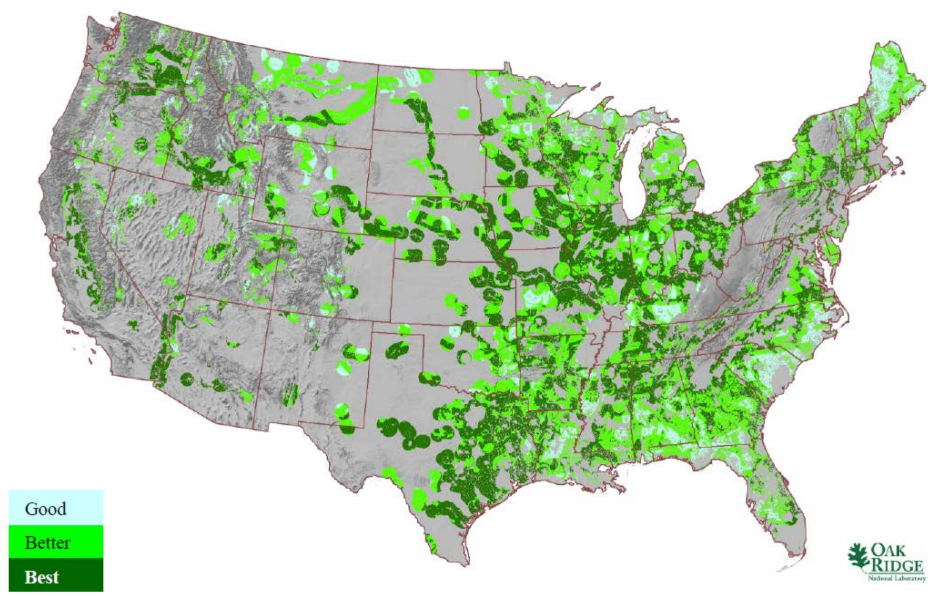

Figure 4-1
ORNL results depicting potentially favorable sites for deployment of SMRs based on multiple siting criteria. [Source: ORNL and USDOE.]

4.5 Land Use Requirements

The physical footprint required for siting new plant deployment represents an important consideration for and feature of lwSMR and advanced reactor systems. Since smaller footprints are an important feature and selling point for many lwSMRs and advanced reactor systems, nominal land area requirements and plant footprints are proposed by developers. Table 4-4 provides lwSMR and advanced reactor site footprints proposed in or derived from publicly available sources. These values should not be considered definitive and are included for

---

[109] Evaluation of Suitability of Selected Set of Coal Plant Sites for Repowering with Small Modular Reactors. Oak Ridge National Laboratory. March 2013. ORNL/TM-2013/109.

illustration purposes to provide insight into land requirements on an order-of-magnitude basis.

As of 2015, the median land area per commercial reactor site in the U.S. is 340 ha (1.3 mi2); this figure is calculated based on 99 operating Generation II LWRs on 59 nuclear plant sites.[110]

While it is not possible to directly compare the values due to the assumptions used and other independent factors, it does appear that the proposed land requirements for siting a range of lwSMR and advanced reactor options are at least an order of magnitude (or 10 times) less than that associated with the current U.S. LWR fleet.

---

110 Nuclear Energy Institute. Land requirements for carbon-free technologies. July 2015. http://www.nei.org/CorporateSite/media/filefolder/Policy/Papers/Land_Use_Carbon_Free_Technologies.pdf?ext=.pdf

Table 4-4
Illustrative Site Land Area Requirements for lwSMRs and Advanced Reactors.

Developer	Design	Plant Configuration	Total Plant Capacity (MWe)	Land Area (hectares)	Land Area (acres)
Composite of U.S. LWR fleet on 59 physically separate sites in 2015[111]	Nominal Generation II GWe plant	Single unit plant	1000	340	830
NuScale[112]	NuScale	12 module plant	600	18	44
Holtec[113]	SMR-160	Single unit	145	1.8	4.5
		Two unit	290	2.4	6
Westinghouse[114]	SMR	Single unit plant	225	6.1	15
General Atomics[115]	EM^2	4 module plant	1060	9.3	23
X-energy[116]	Xe-100	4 module plant	190	4.0	10

[111] *Land requirements for carbon-free technologies*. Nuclear Energy Institute. July 2015. http://www.nei.org/CorporateSite/media/filefolder/Policy/Papers/Land_Use_Carbon_Free_Technologies.pdf?ext=.pdf

[112] M. McGough. *NuScale Power: One year after the DOE award*. Nuclear News. December 2014. p. 60-62.

[113] Holtec International, SMR LLC. 2015. http://smrllc.com/

[114] K. Paserba. *The Westinghouse SMR: Simpler, smaller, and safer*. Nuclear News. December2014. P. 81-84.

[115] R. Schleicher and C.A. Back. *EM^2: A high-efficiency gas-cooled fast reactor*. Nuclear News. December 2014. p. 50-53.

[116] http://www.x-energy.com/

4.6 Water Use and Cooling Requirements

As all conventional nuclear reactor systems must reject heat to the environment based on the total heat generated minus the total converted to useful energy, the primary determinant for cooling requirements is the efficiency with which heat is converted in electrical energy and other energy products. Thus, for similar thermal outputs and thermal energy conversion efficiencies, thermal generation like coal and nuclear should have comparable cooling requirements. Since light-water reactors run at temperatures that are significantly lower than the ones for fossil units, efficiencies are also lower (34 - 36 % vs. 40%) and water requirements will be greater for nuclear electricity on a per MWh basis. In addition, external and highly variable factors including local climate and cooling water temperatures also impact plant thermal conversion efficiency and therefore cooling requirements.[117] Since electrical outputs for nuclear reactor designs are dependent on cooling technology used, climate and cooling water temperature, capacity is frequently quoted for the most limiting conditions, e.g., summer capacity.

Heat rejection to the ultimate heat sink is accomplished with wet cooling, by transferring waste heat to the air via evaporation (and recirculation systems and cooling towers) or to a large water body, such as a river, lake, or ocean (once-through cooling). Once-through wet cooling for Rankine steam cycle plants impose far greater water withdrawals than closed-cycle (recirculating) wet-cooling systems (Table 4-5).[118]

---

[117] *Water Use for Electric Power Generation*. EPRI, Palo Alto, CA: 2008. 1014026.

[118] Comparison of Alternate Cooling Technologies for U. S. Power Plants: Economic, Environmental and Other Tradeoffs. Palo Alto, CA: EPRI; 2004; 1005358.

Table 4-5
Estimated plant cooling water withdrawals for main steam condenser (m^3/MWh)[119].

Power Conversion	Plant Technology	Wet Cooling		Dry Cooling
		Once-Through	Closed Cycle	
Rankine (Steam) Cycle	Coal	95 – 170	2.1 – 3.0	0
	Gas	76 – 130	1.9 – 2.6	0
	Nuclear	130 – 190	2.8 – 3.4	0
Brayton Cycle	Simple-cycle combustion turbine (SCCT)	0	0	0
Combined-Cycle	Natural gas combined-cycle (NGCC)	26 – 45	0.66 – 0.95	0
	Integrated gasification combined-cycle (IGCC)	Not applicable	1.4 – 2.4	0

However, the absolute water consumption is reversed for wet-cooling since once-through systems reject heat to the environment by returning the water inventory to the water source, whereas closed-cycle systems reject heat to the atmosphere via water evaporation. In this respect, NEI reports water usage requirements for light-water reactors of 1.5 m^3/MWh (400 gallons/MWh) for once-through cooling and 2.7 m^3/MWh (720 gallons/MWh) for wet cooling towers.[120]

Wet cooling provides another external vulnerability to plant operators, as thermal discharge limits to streams and lakes may restrict heat rejection rates at certain times of year.[121]

These limits can impact operations during periods of drought and high temperatures. For example, during a particularly acute heat wave in France in 2013, 17 of 58 operating reactors were either de-rated down or shut down temporarily to avoid exceeding thermal discharge limits established for inland water bodies.[122]

---

[119] *Water Use for Electric Power Generation*. EPRI, Palo Alto, CA: 2008. 1014026.

[120] NEI Fact Sheet: *Water Use and Nuclear Power Plants*. Nuclear Energy Institute, November 2013. http://www.nei.org/Master-Document-Folder/Backgrounders/Fact-Sheets/Water-Use-and-Nuclear-Power-Plants

[121] D. Wagman. Water issues challenge power generators. PowerMag. 01 July 2013. http://www.powermag.com/water-issues-challenge-power-generators/

[122] J. Canter. New York Times (online). 20 May 2007. http://www.nytimes.com/2007/05/20/health/20iht-nuke.1.5788480.html?pagewanted=all&_r=0

4.7 Regulatory Frameworks, Design Certification and Licensing

Design certification and licensing are commonly cited as a major barrier for commercial deployment of lwSMRs and advanced reactors.[123,124,125] Water-cooled SMRs are expected to benefit from the established regulatory experience and well-developed framework for larger LWRs due to extensive technology overlap, whereas licensing paths for advanced (largely non-LWR) design concepts are uncertain, undefined or untested in most countries. New design features, operational modes, and target applications and markets introduce new issues that need to be addressed and resolved prior to receiving design certification and operating licenses from regulators. The following section refers extensively to the regulatory process and framework in the United States given the amount of information available and the important role the U.S. NRC plays internationally as a model for independent nuclear regulatory authority. However, it should also be recognized that the challenges and gaps faced will vary by nation. In those countries that have adopted more performance based regulation or have recent experience with diverse commercial reactor technologies, such as the United Kingdom, the path to licensing of lwSMRs and advanced reactors may prove more direct than reflected in the following analysis.

In the United States, the NRC has outlined its plans for exercising and further developing its licensing framework for lwSMRs and advanced reactors by adapting and extending existing regulation and guidance, which it views as sufficiently flexible to accommodate Generation III+ large LWRs, lwSMRs and Generation IV reactors.[126] Based on the interest expressed to the NRC, these activities would focus on (in decreasing order of priority):

1. Design certification and licensing of Generation III+ LWRs;
2. Design certification and licensing of small modular light-water reactors; and
3. Developing a regulatory process for advanced non-light-water reactor designs by building on the current licensing regime and continuing the work under established under joint NRC-DOE initiatives.

This evolutionary, incremental expansion of the U.S. licensing regime to include lwSMRs and advanced non-LWRs is illustrated in Figure 4-2. lwSMRs licensing is a direct extension of the large LWR licensing process. Ongoing activities of

---

[123] *Advanced Reactor Concepts Technical Review Panel Public Report: Evaluation and Identification of Future R&D on Eight Advanced Reactor Concepts, Conducted April – September 2012*. U.S. Department of Energy, Office of Nuclear Energy. Washington, D.C. December 2012.

[124] *Advanced Reactor Concepts Technical Review Panel Public Report: Evaluation and Recommendations for Future R&D on Seven Advanced Reactor Concepts, Conducted March through June 2014*. U.S. Department of Energy, Office of Nuclear Energy. Washington, D.C. October 2014.

[125] Summary of September 1-2, 2015. Nuclear Regulatory Commission and Department of Energy Co-Hosted Workshop on Advanced Non-Light Water Reactors. U.S. Nuclear Regulatory Commission. Washington, D.C. October 1, 2015.

[126] *Report to Congress: Advanced Reactor Licensing*. U.S. Nuclear Regulatory Commission. Washington, D.C. August 2012.

the NRC in cooperation with DOE to support design certification and review of HTGRs under NGNP and SFRs are leveraged to support future and broader applicability to other advanced Generation IV reactor families and variants.

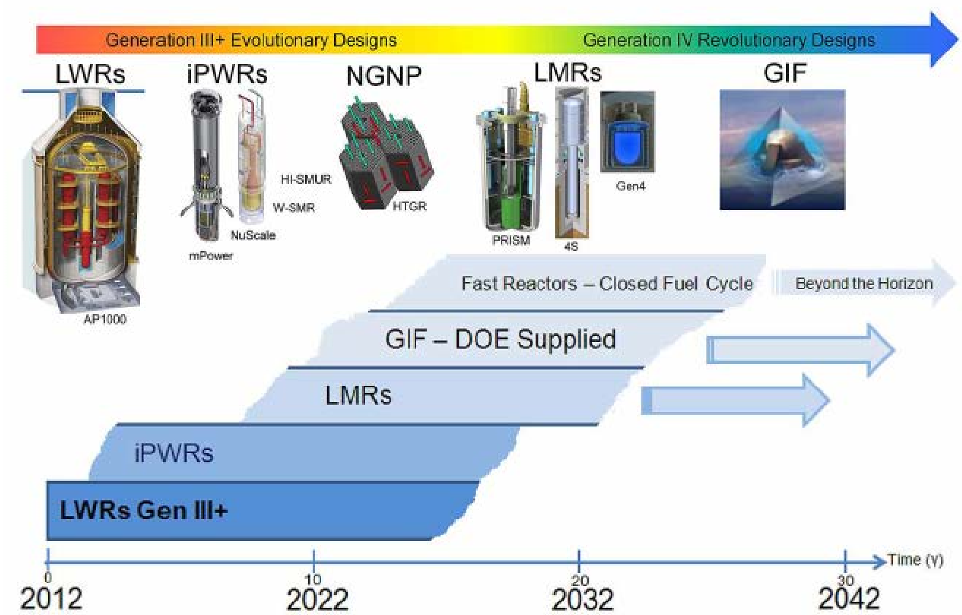

Figure 4-2
U.S. NRC perspective on continuity of lwSMR and advanced reactor licensing with established LWR licensing basis. [Source: U.S. NRC.][127]

4.8 Generation III+ LWR Design Certification and Licensing

The NRC continues to review applications for new reactors with respect to: standard reactor design certifications, early site permits, limited work authorizations, construction permits, operating licenses, and combined construction and operation licenses (COLs) [128] The NRC has certified or is reviewing a number of large (gigawatt-class) advanced LWR designs (Table 4-6). With design certification, the NRC provides formal pre-approval of a nuclear power plant design independent of site-specific construction and operation authorization. Design certifications are valid for 15 years and are renewable.

Licensing of new reactor facilities generally falls under the contemporary 10 CFR 52 process, and three licensees now hold the resulting COLs. Two are actively building Westinghouse AP1000s: Southern Nuclear Operating Company Vogtle with Units 3 and 4 and South Carolina

[127] *Report to Congress: Advanced Reactor Licensing*. U.S. Nuclear Regulatory Commission. Washington, D.C. August 2012.

[128] *New Reactors*. U.S. Nuclear Regulatory Commission. http://www.nrc.gov/reactors/new-reactors.html. September 2016.

Electric & Gas with V.C. Summer with Units 2 and 3. Detroit Edison (DTE) received its COL on May 1, 2015 for Fermi Unit 3, a GE-Hitachi Economic Simplified Boiling Water Reactor (ESBWR); however, construction plans are currently on hold. Meanwhile, a full power license was granted on October 22, 2015, to TVA for the operation of Watts Bar Unit 2 under 10 CFR Part 50. Construction of Watts Bar 2, a Generation II design, was halted in 1985 and resumed in 2007. The unit was connected to the grid in 2016 and is currently operating at full power.

Table 4-6
U.S. Nuclear Regulatory Commission Design Certification for Generation III/III+ Advanced Light Water Reactors.[129]

Design	Applicant	Design Certification Status
Advanced Boiling Water Reactor (ABWR)	General Electric (GE) Nuclear Energy	Issued
ABWR Design Certification Rule (DCR) Amendment	South Texas Project Nuclear Operating Company	Issued
System 80+	Westinghouse Electric Company	Issued
Advanced Passive 600 (AP600)	Westinghouse Electric Company	Issued
Advanced Passive 1000 (AP1000)	Westinghouse Electric Company	Issued
Economic Simplified Boiling-Water Reactor (ESBWR)	GE-Hitachi Nuclear Energy	Issued
U.S. EPR	AREVA NP, Inc.	Under review[a]
U.S. Advanced Pressurized-Water Reactor (US-APWR)	Mitsubishi Heavy Industries, Ltd.	Under review
ABWR Design Certification Renewal	Toshiba Corporation Power Systems Company	Under review
ABWR Design Certification Renewal	GE-Hitachi Nuclear Energy	Under review
Advanced Power Reactor 1400 (APR1400)	Korea Electric Power Corporation and Korea Hydro & Nuclear Power Co., Ltd.	Under review

[a]The U.S. EPR design review has been suspended indefinitely at the request of the vendor, AREVA.[130]

---

[129] *Design Certification Applications for New Reactors*. U.S.NRC. Washington, D.C. Updated July 9, 2015. http://www.nrc.gov/reactors/new-reactors/design-cert.html

[130] World Nuclear News. *US EPR Plans Suspended*. 6 March 2015. http://www.world-nuclear-news.org/RS-US-EPR-plans-suspended-0603157.html

4.9 lwSMR Design Certification and Licensing

The new features, components and approaches introduced to differentiate lwSMRs and advanced reactors from large LWRs in terms of economics, deployability, safety, operation and maintenance also introduce gaps in regulatory knowledge and precedence. For the leading SMRs, primarily iPWRs, these elements include:

- Integrated primary system designs
- New passive safety system performance and reliability
- New mechanistic bases for establishing accident source terms
- New licensing basis events (e.g., for severe accidents)
- Long-lived cores and elimination of onsite refueling
- Reduced plant staffing requirements (through simplified operation and maintenance)
- Reduced control room requirements (i.e., allowing for multi-module control by a single control room, thus reducing the number of licensed control room operators per unit)
- Reduced emergency planning zone requirements

However, in spite of these regulatory gaps, the U.S. NRC is on record affirming its readiness to review light-water SMR license applications.[131] Table 4-7 reflects the NRC's record of early pre-application engagement with SMR developers and licensees.

Table 4-7
Reported pre-application engagement of lwSMR developers and potential licensees with the U.S. NRC.[132]

Design/Site	Application Type	Applicant
NuScale	Design Certification	NuScale Power, LLC
BWXT mPower™	Design Certification	Babcock & Wilcox (B&W) mPower, Inc.
Holtec SMR-160	Design Certification	SMR LLC, a Holtec International Company
Westinghouse SMR	Design Certification	Westinghouse Electric Company
Clinch River Site Roane County, TN	Early Site Permit	Tennessee Valley Authority (TVA)

[131] *Status of the Office of New Reactors Readiness to Review Small Modular Reactor Applications*. U.S. Nuclear Regulatory Commission. Washington, D.C. August 28, 2014. SECY-14-0095.

[132] *Advanced Reactors and Small Reactors*. U.S. Nuclear Regulatory Commission. Updated September 8, 2015. http://www.nrc.gov/reactors/advanced.html

The Tennessee Valley Authority (TVA) is preparing for an Early Site Permit application for the US Nuclear Regulatory Commission for its Clinch River site in Roane County, Tennessee. The application references a generic plant parameter envelope, not a specific technology. Submittal of the ESP application is expected by late 2016 followed by selection of the reactor technology, expected to be an SMR design, in mid-2017.[133]

4.10 Generation IV Design Certification and Licensing

In response to growing interest in advanced reactor concepts, the U.S. NRC has also expressed its willingness to consider non-LWR designs and strongly encourage all advanced reactor developers to engage early with NRC staff. And while the lack of an appropriate regulatory framework is the most commonly cited barrier to commercialization of advanced reactors in the United States among the developer community, the NRC insists the current framework is adequate to handle non-LWR designs while also acknowledging that new regulatory guidance for reviewing and licensing non-LWR technologies is needed to support NRC staff and the adaptation of the current process.[134]

A major barrier for commercialization is the development of principal design criteria to support application for a construction permit, design certification, or construction and operating licensing under both Part 50 and Part 52 processes. To address this concern, DOE and NRC are working together under a joint initiative to address regulatory information and process gaps. Under this two phase initiative, DOE led review and analysis efforts to develop guidance for developing principal design criteria for advanced reactors modeled after the 10 CFR 50 Appendix A General Design Criteria (GDC) for LWRs, which culminated in a final report transmitted to the NRC in December 2014. [135] NRC is now proceeding with developing of regulatory guidance for advanced reactors, with a preliminary regulatory guide to be issued by the end of 2016. The result is intended to be a complementary description of how advanced reactor designs intend to address the safety principles captured in 10 CFR 50 Appendix A as LWR-based GDCs.

---

[133] *Tennessee Valley Authority (TVA) Clinch River Site Early Site Permit (ESP) Application*. U.S. Nuclear Regulatory Commission. Updated October 5, 2015. http://www.nrc.gov/reactors/advanced/clinch-river.html

[134] *Report to Congress: Advanced Reactor Licensing*. U.S. Nuclear Regulatory Commission. Washington, D.C. August 2012.

[135] *Guidance for Developing Principal Design Criteria for Advanced (Non-Light Water) Reactors*. Idaho National Laboratory, Idaho Falls, ID. December 2014. INL/EXT-14-31179. Revision 1

Section 5: lwSMR and Advanced Reactor Commercial Applications

5.1 Key Markets for lwSMRs and Advanced Reactors

There are two general classes of applications envisioned for lwSMRs and advanced reactors. The first set, which can be loosely characterized as the “fit for purpose and scale” grouping, comprises non-traditional electricity markets and non-electricity applications that are not well served by larger nuclear units. These include developed and developing markets.

Smaller generating units may be attractive as replacement generation for retiring fossil units that, by virtue of age, tend to be smaller in capacity and therefore would likely present one or more important siting restrictions in terms of grid connection, land area, and water supply. Also, nuclear power plants equipped with multiple SMR units can offer better flexibility for utilities operating in markets with large shares of variable renewable, generating resources, or operating in small grids.[136]

Non-electricity applications, such as those reliant on high-quality process heat, are also not well served by the current, larger capacity nuclear options. Smaller generation options, especially those requiring minimal maintenance and long-life cores, are also attractive options for remote locations where grid connections are not available, such as islands, isolated towns and extractive industry (fossil fuel recovery and mining) locations where reliance on delivery of liquid fuels is undesirable and costly. Smaller generation capacity may also be desirable in regions and countries where the grid infrastructure is new, non-existent, or emerging.

A second market potentially favoring lwSMR and advanced reactor attributes encompasses customers valuing incremental investment and capacity over economy of scale, for which the large capital investment represented by a GWe-scale nuclear unit presents an unacceptable risk or entry barrier. In this regard, lwSMRs would be in direct competition with conventional nuclear and other generation capacity, and the principal commercial driver for construction of a small LWR or advanced reactor (versus one or more larger units) is the smaller and more flexible capital investment required for bringing new generation

---

[136] *OECD / NEA Report,* Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment, 2016, http://www.oecd-nea.org/ndd/pubs/2016/7213-smrs.pdf

capacity online and the smaller incremental addition of capacity that can be brought online to better match demand growth.

A third, more aggressive case has been made insisting that advanced reactors can compete with large nuclear and other generation options on all fronts by offering new attributes and capabilities, less-capitally intensive and more incremental capacity addition, and cost-competitive energy/products – principally through gains in thermal efficiency with very-high temperatures (i.e., 850 °C and above) that offset other cost increases.[137] However, it is also generally acknowledged that advanced systems with these attributes are less mature and in need of substantial investment in RD&D and testing infrastructure to de-risk and demonstrate use of new materials, fuels and energy conversion technology at the required temperature range.

The market for lwSMRs and advanced reactors is highly-uncertain but also potentially large. This market includes countries with nuclear plants and those considering nuclear for the first time (as well as a few nations considering a return to nuclear power). Of the countries that have not operated a grid-connected commercial nuclear power plant, the IAEA considers 33 to be interested in or actively pursuing nuclear power.[138] By 2030, the IAEA projects nuclear capacity to grow by 29 - 328 GWe for its low- and high-growth scenarios, respectively. The World Nuclear Association estimates that as many as 45 countries (or non-governmental entities therein) are considering nuclear for the first time.[139]

A 2014 report by the UK's National Nuclear Laboratory (NNL) evaluates the potential global market for near term deployment of lwSMRs in terms of viability and scale for the purpose of informing possible roles for and investment by UK government and industry as a new business opportunity to benefit the nation.[140] For a very limited "niche only" market for lwSMRs for grid connected electricity generation, the NNL report found a very limited market totaling 5 GWe of capacity through 2035 valued at 32 – 40 billion USD.[141] Under more optimistic assumptions where lwSMRs compete favorably with large nuclear units and other forms of generation, the estimated worldwide market for lwSMRs expands to 65

---

[137] *Hearing on Nuclear Energy Innovation and the National Labs.* May 13, 2015. U.S. House of Representatives. Committee on Science, Space and Technology Subcommittee on Energy. 114th Congress, 1st Session. Washington, D.C. (Testimony of John A. Parmentola, General Atomics). http://docs.house.gov/meetings/SY/SY20/20150513/103447/HHRG-114-SY20-Wstate-ParmentolaJ-20150513.pdf

[138] *International Status and Prospects for Nuclear Power 2014. Report by the Director General.* IAEA Board of Governors and General Conference. August 4, 2014. GOV/INF/2014/13-GC(58)/INF/6.

[139] *Emerging Nuclear Energy Countries*. World Nuclear Association. Updated November 2015. http://www.world-nuclear.org/info/Country-Profiles/Others/Emerging-Nuclear-Energy-Countries/

[140] Small Modular Reactors (SMR) Feasibility Study. National Nuclear Laboratory. December 2014.

[141] Calculated for 2012 pounds assuming an average currency conversion rate of 1.6:1 USD per British pound.

– 85 GWe worth approximately 400 – 640 billion USD. This expanded lwSMR market scenario includes countries meeting a number of with sufficient:

- Population and per capita electricity demand;
- Gross domestic product and purchasing power;
- Energy security needs driven by limited domestic fuel resources;
- Non-proliferation credentials; and
- Political stability.

Table 5-1 breaks this expanded global market down by region and countries. The list deliberately excludes several prominent countries with existing nuclear programs, e.g., Japan, Germany, France and South Korea. Japan is deemed to be an unlikely market for lwSMRs in the near-term given its unique set of post-Fukushima challenges associated with restart of its existing nuclear fleet combined with its high population density and highly developed integrated grid infrastructure compatible with large central station generation capacity. Germany is considered an unlikely candidate for lwSMRs and advanced reactors construction for the foreseeable future due to its policy to move away from all nuclear generation. Both France and South Korea continue to present conditions favoring large nuclear plant deployment, due to their already existing infrastructure and supply chains.

Table 5-1
Upper bound estimate of potential global lwSMR market assuming favorable economics as an electric power generation option. [Source: Adapted from 2014 UK National Nuclear Laboratory study.][142]

Region/Country	Estimated Generation Capacity Market (MWe)
North America	
Canada	1650*
Mexico	1500
United States	15000
South America	
Argentina	2900*
Brazil	6200
Chile	300
Europe	
Continental Europe	2140
United Kingdom	7000

[142] *Small Modular Reactors (SMR) Feasibility Study*. National Nuclear Laboratory. December 2014.

Table 5-1 (continued)
Upper bound estimate of potential global lwSMR market assuming favorable economics as an electric power generation option. [Source: Adapted from 2014 UK National Nuclear Laboratory study.]

Region/Country	Estimated Generation Capacity Market (MWe)
Africa	
South Africa	600
Tunisia	160
Middle East	
Middle East	1330
Asia	
China	15000
India	4800
Near East	1500
Russian Federation	10000
Southeast Asia	1125
Australia	
Australia	2000*

*Countries where export market may be limited due to either a moratorium on new construction or strong domestic design preference.

5.2 Ongoing and Future Developments

The challenges and opportunities associated with development and deployment of new nuclear generation technologies limit what can be state conclusively about the future role of nuclear in a specific country or region. However, the evidence does support a number of observations:

- While a nuclear "renaissance" has not materialized in the United States and other western countries as expected, a robust global market exists for construction for large advanced (GEN III) light water reactors, especially in Asia. And limited new construction of ALWRs does continue in the West.
- Limited deployment of small modular LWRs is beginning with construction of CAREM-25 in Argentina and barge mounted twin-unit KLT-40S in Russia. Meanwhile, licensing of the NuScale iPWR in the United States continues.
- Demonstration of GEN IV reactor technologies is occurring in a handful of countries. For the sodium-cooled fast reactor family, Russia has now begun full power operation of the BN-800 SFR and India is nearing operation of its PFBR. China is supporting multiple advanced reactor development and demonstration programs, and operation of its demonstration-scale HTR-PM high-temperature gas-cooled reactor is imminent.

- Interest in lwSMRs and GEN IV technology continues even in the United States where operating large LWRs face early retirement due to adverse market conditions.

Continued progress in RD&D and new build programs for lwSMRS and advanced reactors will be heavily dependent on successful licensing, construction and operation of the various demonstrations, first-of-a-kind commercial units and other early technology adopters. Notable indicators of this progress worth monitoring in the near-term include:

- Completion and operation of the CAREM-25 demonstration reactor in Argentina.
- Submission of the first U.S. lwSMR license application for construction of a multi-unit NuScale nuclear plant by the UAMPS consortium.
- Full power operation of the BN-800 SFR in Russia.
- Completion of the dual-unit HTR-PM demonstration HTGR in China.
- Resolution of key licensing issues in the U.S. and other markets that could serve as leading indicators for commercialization of lwSMR and advanced reactor designs.
- Evolution of the expanding field of entrepreneurial, privately-backed advanced reactor developers in North America and beyond.
- Development of more credible cost estimates and timelines for commercial deployment of lwSMRs and advanced reactors.
- Development by EPRI of an Owner-Operator Requirements Document (ORD) for Advanced Reactors.

Successful development, demonstration and deployment of more advanced GEN IV designs will be influenced by outcomes of more aspirational programs and efforts globally, including:

- Planning for prototype four-unit HTR-PM plan is underway. With the parallel development of pebble fuel fabrication facilities, full commercialization and possible export of the HTR-PM technology appears feasible by the mid-2020s.
- Russia continues to pursue sale of two BN-800 SFRs to China, which would represent commercial deployment of this GEN IV technology.
- South Korea is pursuing a viable export market for its SMART lwSMR, with possible construction of the FOAK in Saudia Arabia followed by sales of additional units in the region.
- Work on modifying existing and developing new regulatory frameworks and processes to enable predictable and efficient permitting, design certification and licensing of non-LWRs.
- Successful outcomes from continued U.S. government (DOE) support could help accelerate the maturation of private sector designs.

Successful commercial deployment of new nuclear technologies will be heavily influenced if not enabled by, developments in related non-affiliated disciplines that include:

- Advanced power conversion and hybrid systems;
- Advanced materials; and
- Other cross-cutting technologies.

Finally, developments in the realm of policy will also have significant impacts on the commercial viability of new nuclear. Key non-technical areas worth watching include:

- Emergence of durable and effective carbon pricing and markets;
- Reformed electricity and energy market pricing and incentives (e.g., for capacity);
- Expanded and sustained interest from traditional utilities and other potential owner/operators as potential future technology customers.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

Program:

Technology Innovation

3002009413

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com