The Nuclear Mission in an Integrated, Carbon-Free Energy Future

By Sherry BERNHOFT
Senior program manager for Strategic Programs and Long-Term Operations at the Electric Power Research Institute (EPRI)
Andrew SOWDER
Technical executive in the Advanced Nuclear Technology program at the Electric Power Research Institute (EPRI)
and Robert AUSTIN
Senior program manager for the Electric Power Research Institute's (EPRI), new Nuclear Plant Modernization initiative

As the global community strives to curb carbon emissions from the energy sector, focus has sharpened on the role nuclear energy can play in the effort throughout the 21st century. While the light water reactor fleet provides the nuclear generation backbone for meeting future capacity needs and emission goals, more than half of the world's nuclear power plants have surpassed 30 years in service.

The Electric Power Research Institute (EPRI), in collaboration with research entities around the world, helps turn the world's carbon neutrality challenges into opportunities. EPRI's work delivers research to answer key questions about modernization efforts that can provide safe and cost-effective life extensions for long-term operation, increase operational flexibility to support stable power grid dynamics, reduce nuclear power plant operating costs, and the examine the latest reactor technologies for more viable new nuclear power plant construction.

Introduction

As the global community strives to curb carbon emissions from the energy sector, focus has sharpened on the role nuclear energy can play in the effort. In May of 2019, the International Energy Agency (IEA) published its first report in nearly two decades addressing nuclear power. Titled "Nuclear Power in a Clean Energy System", the report identified nuclear plants as a "the largest source of low-carbon electricity in advanced economies as a whole" (IEA, 2019) and concluded that "a range of technologies, including nuclear power, will be needed for clean energy transitions around the world" (IEA, 2019).

With more than 2,500 TWh produced at nuclear power plants worldwide in 2018 (WNA, 2019), the nuclear industry is playing a large role in the energy landscape. Last year, nuclear generated 10% of the world's total electricity and was second only to hydro in global low-carbon power production (IEA, 2019). In fact, nuclear now accounts for 63% of the carbon-free power in the United States (WNA, 2019).

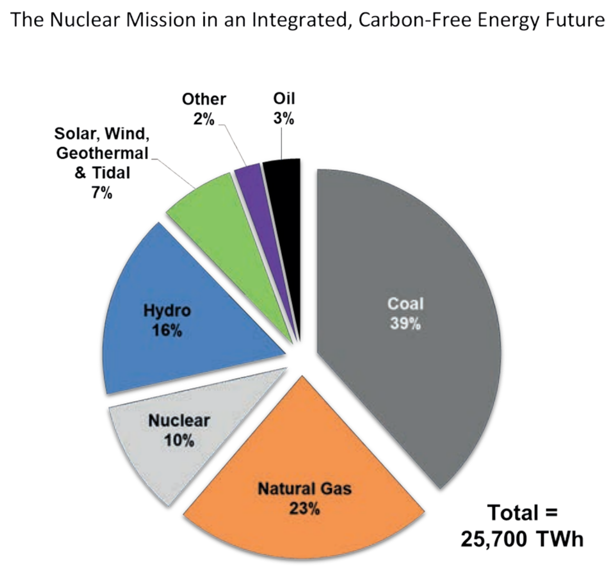

Figure 1. World electricity generation by source in 2018 [Source: IEA, 2019b).
Reference: IEA (2019b). "Electricity Information 2019."

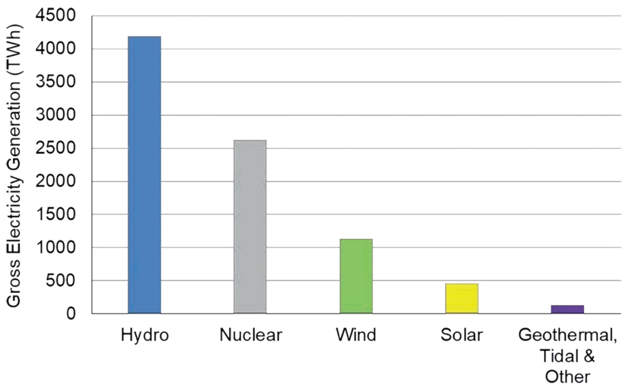

Figure 2. Global electricity generation from low-carbon sources [Source: IEA, 2019].
Reference: IEA, 2019. "Electricity Information: Overview (2019 edition)."

Nuclear power offers significant potential to address climate change throughout the 21st century. However, because nearly 60% of the world's more than 450 nuclear power plants in operation today have been in service more than 30 years, efforts to modernize plant equipment and extend operation beyond licensed lifetimes are paramount.

The industry faces other challenges as well. While nuclear plants still produce a large portion of global low-carbon energy, growth has slowed in much of the western world. The latest nuclear additions have been in China, South Korea and Russia.

According to the IEA article, "Without additional nuclear, the clean energy transition becomes more difficult and more expensive – requiring $1.6 trillion of additional investment in advanced economies over the next two decades" (IEA, 2019).

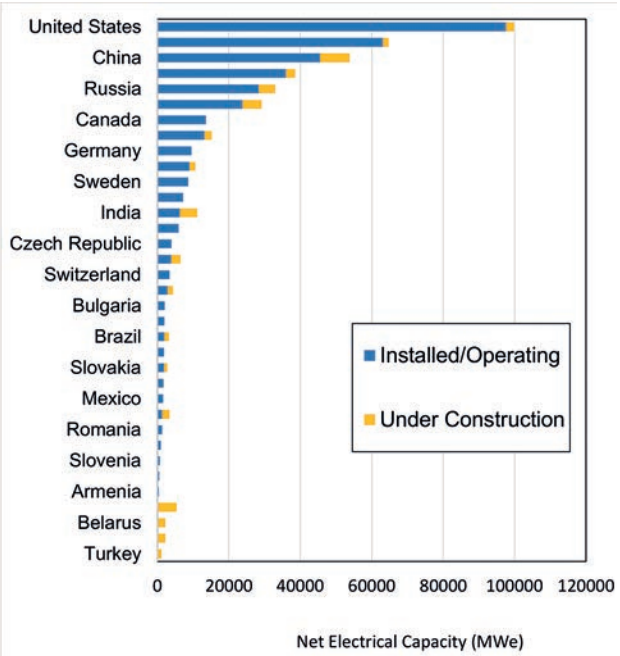

Figure 3. Nuclear electricity generation capacity in 2019 by country for existing reactors (in blue) and units under construction (orange) [Source: IAEA PRIS Database, 2019].

Making the most of industry opportunities

The IEA's nuclear report makes policy suggestions for sustaining the nuclear power industry as an important part of the carbon neutrality equation. This means overcoming a variety of industry challenges by improving power plant economics, extending operating life, and supporting the ever-changing power grid with flexible operation.

The Electric Power Research Institute (EPRI), in collaboration with research entities around the world, turns these industry challenges into opportunities by delivering the research needed to help nuclear power plant operators answer these key questions:

- How can plant operating life be safely and cost-effectively extended?
- How can modernization efforts reduce overall plant operating costs?
- How can operational flexibility help stabilize power grid dynamics?
- How can the latest reactor technologies make new nuclear plant construction more viable?

Modernizing for reduced operating costs

When the cost of generating nuclear power is greater than the cost of purchasing power on the open market, nuclear power plant viability is on the line. So in 2018, nuclear industry stakeholders and EPRI launched the Nuclear Plant Modernization initiative to explore the potential to preserve nuclear power as a carbon-free, safe, reliable energy resource. In the initial phase of this initiative, EPRI and other organizations collaborated to determine the feasibility of reducing non-fuel operating costs through the application of existing modern technologies.

Preliminary analysis suggests that plant operators who equip their facilities with updated technologies and improved processes – such as automation, digital controls, artificial intelligence, and virtual reality tools – can reduce operating costs by 25% or more. "Automated power plants offer enormous cost-reduction potential – much greater than many in the industry realize", said Robert Austin, EPRI's lead for the Nuclear Plant Modernization initiative. He adds that further research may well reveal that plant modernization efforts could reduce operating costs by as much as 50%, without the need for heavy construction. A cost reduction of this magnitude could be sufficient to return many plants to economic viability.

While safety-related digital systems are the norm in such countries as France, South Korea and China, many nuclear plants are not so modern. A number of plants still use manual work processes along with either analog controls or older digital controls, making them more costly to operate. "By following suit with other energy industries, nuclear plant operators can use digital controllers and computers to significantly cut labor requirements for inspections and other tasks required for regulatory and industry compliance", said Austin.

Other exciting digital technologies being studied as part of the Nuclear Plant Modernization initiative include artificial intelligence (AI) and virtual reality (VR). More sensors allow for greater data collection and provide the opportunity for advanced AI techniques to deliver insight regarding equipment strengths and potential vulnerabilities. Advanced technology can tap into a rich source of new and previously stored data to predict potential failures even earlier. And, because the nuclear industry shares a lot of data, EPRI is using analytics to examine large data sets and report on best practices based on observed patterns and trends.

Research on VR also has produced promising results. One project used VR to make hands-on turbine training easier, less costly, and more effective than standard training. In another project, inspection data was overlaid onto actual pipe welds in augmented reality, allowing for much more effective flaw visualization.

Another aspect of modernization involves task automation – replacing manual time-based tasks with automatic condition-based tasks. EPRI's research explores condition-based maintenance and has effectively demonstrated automation of water chemistry sampling for increased efficiency and cost savings. The initiative also is researching how drones or robots could perform radiation monitoring tasks.

EPRI's efforts to assess the feasibility and economic viability of modernization based on existing technologies are expected to be completed this year. In 2020 and 2021, the initiative will focus on providing technology demonstrations, common information models, standardized implementation methods, tools to inform decisions on plant capital investments, and detailed business cases to be published in a plant modernization handbook to help guide interested utilities.

"It could be that the cheapest way to guarantee and expand carbon-free electricity generation is modernizing existing nuclear power plants", said Austin. "Other industries have reduced their costs in this fashion. Why not nuclear?"

Extending plant life for long-term operation

The recent IEA report underlines the importance of extending the lifetime of nuclear power plants in getting the clean energy transition "back on track" (IEA, 2019). According to Sherry Bernhoft, EPRI's senior program manager for its Nuclear Power Plant (NPP) Long-Term Operations (LTO) program, although they may require significant investment in plant refurbishments, plant life extensions are much more cost effective than building new plants. "That's why EPRI started researching LTO back in 2010, drawing on a broad range of technical expertise as well as decades of data, observation and experiences collected in materials, engineering, and plant operations", said Bernhoft.

Many of the world's aging nuclear reactors are facing the critical decision of extending their operating licenses. In the United States, the Nuclear Regulatory Commission (NRC) grants an initial 40-year operating life followed by 20-year renewal periods. Today, more than 90% of US plants have had their licenses extended from 40 to 60 years. In many other countries, reviews and extensions are tied to the International Atomic Energy Agency (IAEA) Periodic Safety Review (PSR) process.

In the US, plants are pursuing second license renewals that extend power plant life from 60 to 80 years. "Research findings to date indicate that life extension of nuclear plants beyond 60 years, and out to 80 years, is technically feasible", said Bernhoft. To achieve the goal of safe and reliable long-term operations, plant owners and operators need to implement aging management programs (AMPs). Robust AMPs include the identification of material degradation, inspection techniques, evaluation methodology, and repair or replacement criteria.

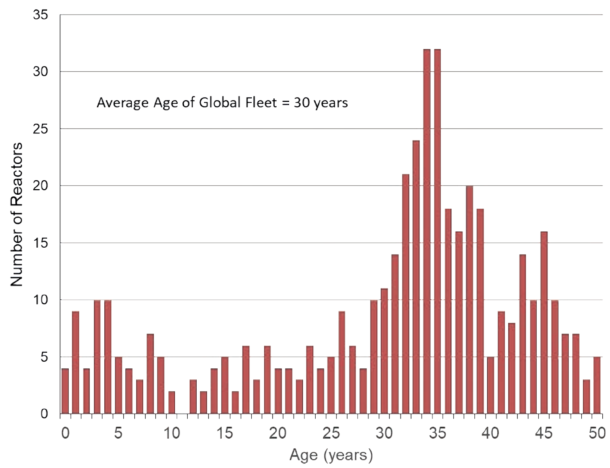

Figure 4. Age profile of global nuclear reactor fleet [Source: IAEA PRIS Database, 2019].
Reference: IAEA PRIS Database, 2019.

Because nuclear plants in the US are on average five to 10 years older than nuclear plants in Europe and Asia, their operating experience and management philosophy informed the development of the first set of AMPs required for license renewal by the NRC. Those AMPs helped create the US Generic Aging Lessons Learned (GALL) report, which became a starting point and forerunner for the IAEA's International Generic Aging Lessons Learned (IGALL) report. The IGALL serves as the framework in many countries for nuclear power plant extended operations around the world.

The AMPs in the IGALL, now in its third revision, are reviewed and updated regularly based on evolving operating experience, new research results and inspection findings, and the sharing of global operating experience. Broad international collaboration remains essential to ensure a sound technical foundation for the life extension of nuclear power plants.

EPRI, in collaboration with research entities around the world, has played a vital part in studying and reporting on the technical details that nuclear power plant operators need to make informed decisions related to plant life extension and refurbishments. Its research has provided a scientific and technical foundation for AMPs that address safety, performance, and cost. Bernhoft notes that more than 125 different EPRI research reports were referenced in the IGALL report.

"EPRI's LTO research has focused on two key areas: components critical to nuclear power plant safety and systems or equipment that are hard to replace", explained Bernhoft. These include the reactor pressure vessel, reactor internals, large concrete civil structures, and the electrical cable system. The goal is to help power plant operators avoid cost-prohibitive component replacements that could lead to plant closure.

Stabilizing the grid with flexible operation and storage solutions

As the world's dependency on renewable sources builds, the IEA report also focuses on nuclear plant flexibility. The predictable energy system of the past – predominantly based on coal, nuclear, and gas plants – is morphing into a more dynamic end-to-end power system. For instance, with the addition of wind and solar farms, nuclear power can support grid stability, adjusting power output to deal with the seasonal and day-to-day variations that renewable energy brings. In addition, the energy system of today also must respond to the effects of a growing number of electric vehicles and changes to the transmission system.

Bernhoft who also is EPRI's senior program manager for its NPP Flexible Operations initiative, states that, "In France, nuclear power plants have been setting an example for flexible operation since the 1980s, but much of the rest of the world is still working hard to catch up." In 2012, proactive research under the Flexible Operations initiative was started to understand the impacts to plant operation associated with varying power output. This research has helped shift the nuclear power plant paradigm from baseload operation to much more flexible operation that can better accommodate the integration of growing renewables capacity into the electrical system.

Based on its research, EPRI has published best practices for plants that want to operate more flexibly with manageable impacts. Findings point to the need for changes to maintenance schedules and practices, including more frequent chemistry monitoring and core internals inspections.

Future research is targeted to integrated energy systems, with one possible application using electrical power from a nuclear asset to produce and store hydrogen during periods of over-production from renewables. This type of application will allow the nuclear plant to provide valuable grid services, limit the curtailment of renewables and produce another potential source of revenue for the plant operator.

Exploring small modular reactor and advanced reactor technologies

More than a decade ago, there were great expectations for a "nuclear renaissance" yielding new fleets of advanced light water reactors (ALWRs) in the US and globally. While the anticipated number of new plants coming online in the US and Europe has dwindled to a handful, a renaissance has indeed occurred, and continues in China and other Asian countries. "While these newer plants look a lot like the rest of the fleet, many are 'Generation III' plants that offer enhanced safety through the incorporation of passive systems using natural circulation and large inventories of water", said Andrew Sowder, EPRI's technical executive for its Advanced Reactors initiative. "This new generation of plants was also intended to offer improved economics through standardization and simplicity." However, construction delays and escalating costs have undermined the economics and competitiveness of these massive plants in the West.

The IEA's nuclear report makes clear the importance of supporting innovation in lower cost reactor designs that can be put into operation more quickly. These newer reactors also need to offer better operating flexibility to support growing renewable capacity in the grid.

EPRI's Advanced Nuclear Technology (ANT) program has been tracking progress made on light water small modular reactors (SMRs). SMRs potentially offer favorable alternatives to the traditional large nuclear plant, including reduced financial risk per unit and improved licensing due to factory-based manufacturing and modular transportation and construction. "These units have much smaller footprints, with output measured in hundreds – rather than thousands – of megawatts, and also offer utilities right-sized options for providing new generation for regions and countries with smaller grids and for repowering decommissioned coal plant sites", explained Sowder. "Avoiding the need for a huge piece of property and new transmission infrastructure makes for a much more attractive, lower-risk option for many utilities."

A major focus of the ANT program over the past two decades has been to support the design, licensing, and deployment of ALWRs. A key outcome of this collaborative effort is EPRI's Utility Requirements Document (URD), which provides a comprehensive set of design requirements to help utilities deploy a third generation of robust nuclear plants that are simpler and offer increased safety margins. Updated in 2014, the URD now includes research on light water SMR technologies. "EPRI's URD provides the reactor development community with a blueprint to follow to make sure that their SMR products align with the needs of the utilities and the industry", said Sowder.

Recently, EPRI has focused its research on innovative materials and advanced manufacturing techniques needed to fully realize the benefits of factory fabrication of SMR reactor pressure vessels. As part of this Advanced Manufacturing project, EPRI researchers funded by the US Department of Energy (DOE) and in collaboration with UK manufacturers, suppliers, and NuScale Power, are examining new tools and methods such as powder metallurgy, electron beam welding, and additive manufacturing (also known as 3D printing) that improve the quality and speed of the manufacturing process – allowing reactor vessels to be built in months instead of years, while cutting costs by as much as 40%. In another study, a team looked at ways to reduce operating costs through chemistry automation programs. By simplifying processes and reducing manual operations, corrosion risks can be reduced. “This effort has led to specific projects that are now being demonstrated at operating plants”, said Sowder. “Another thing we see in our research is a lot of cross-fertilization. For instance, research and technologies for new plants can also benefit existing plant initiatives such as the Nuclear Plant Modernization initiative.”

Finally, EPRI’s ANT team is looking beyond current Generation III and SMR technology to more advanced non-LWR reactor technologies that go back to the drawing board to examine higher temperature and lower pressure operation using new technologies, coolants, and fuels. “EPRI always has its eye on the next technology coming down the line,” said Sowder. While Generation IV or advanced reactors have yet to be commercialized, these new designs have the potential to offer substantial improvements in terms of natural resource utilization, inherent safety, proliferation resistance, and security. Of course, they also will need to be economically competitive if their potential for delivering scalable, dispatchable, energy-dense, and non-emitting generation is to be realized. “For instance, we likely will see advancements in the use of nuclear heat for industrial purposes as well as the production and storage of hydrogen for added grid flexibility”, Sowder said.

Conclusions

When we consider tomorrow’s energy landscape, we likely will face a less forecastable, and more dynamic power system. It seems clear, however, that whatever the future brings there will be a role for nuclear well into the 21st century. The light water reactor fleet provides the nuclear generation backbone for meeting capacity needs and emission goals.

Meanwhile, many power plant owners will focus on safely and cost-effectively extending equipment life for continued long-term operation, modernizing plants for improved economics, and enhancing operational flexibility to help stabilize power grid dynamics. In the medium- and long-term, advances in reactor technologies should make new nuclear plant investment more viable, potentially bringing on the next nuclear renaissance.

Bibliography

IEA (2019), “Nuclear Power in a Clean Energy System”, p. 80, https://www.iea.org/publications/nuclear/

IEA (2019), “Nuclear Power in a Clean Energy System”, p. 3.

World Nuclear Association (2019), “Nuclear Power in the World Today”, https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

About EPRI’s Research Programs

EPRI, established in 1973, is an independent, nonprofit, collaborative organization that conducts research and development (R&D) relating to generation, delivery and use of electricity for the benefit of the public. Today, more than 350 reactors worldwide, representing 79% of the world’s commercial nuclear units, participate in EPRI’s nuclear sector programs. Research efforts are enhanced through collaboration with various global entities, including the IAEA, OECD-Nuclear Energy Agency (NEA), Électricité de France (EDF) and its Material Aging Institute, World Association of Nuclear Operators (WANO), Central Research Institute of Electric Power Industry (CRIEPI) in Japan, and the US DOE.

EPRI Product References

Nuclear Plant Modernization
The Economics of Nuclear Plant Modernization in U.S. Markets, Product ID: 3002014737, January 2019.
Common Design Package for Wireless Ultrasonic Sensors and Associated Equipment, Product ID: 3002015806, July 2019.
Digital Engineering Guide: Decision Making Using Systems Engineering, Product ID: 3002011816, October 2018.

Long-Term Operations
2018 Update to EPRI Product Mapping to IAEA International Generic Aging Lessons Learned (IGALL) Management Program Categories, Product ID: 3002013053, November 2018.

Flexible Plant Operation
Executive Summary of Lessons Learned from Transitioning to Flexible Operations, 2014-2018, Product ID: 3002012086, September 2018.

Advanced Nuclear Technology
Advanced Light Water Reactor Utility Requirements Document, Revision 13, Product ID: 3002003129, 2014.
Using Technology for Staff Optimization, Improved Effectiveness, and Cost Reduction, Product ID: 3002007071, March 2016.
Assessment of Automation Technologies to Reduce Chemistry and Radiochemistry O&M Costs, Product ID: 3002010493, December 2017.

IEA (2019), “Nuclear Power in a Clean Energy System”, p. 3.

World Nuclear Association (2019), “Nuclear Power in the World Today”, https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

IEA (2019), “Nuclear Power in a Clean Energy System”.

IEA (2019), “Nuclear Power in a Clean Energy System”, p. 3.