Electric Power Research Institute: Expanding the Concept of Nuclear Flexibility for the Current Fleet and the Next Generation of Advanced Reactors

Prepared by Andrew Sowder, Sherry Bernhoft, and Dan Moneghan, Electric Power Research Institute

1.1 Introduction

Changing electricity economics and generation portfolios are driving utilities to reconsider the manner in which current nuclear power plants (NPPs) are operated. In the United States where NPPs traditionally have been operated for base load power generation, many nuclear units have transitioned to flexible operations, such that reactor power levels are adjusted over a limited range to meet anticipated changes in power grid requirements. This departure from base load operation has increased sharply with increasing penetration of variable generation and grid congestion in many regions of the United States.

Flexible operation is an established paradigm for existing reactor technology, describing any mode of operation that is not base load (EPRI 2014a; Lockhov 2011). While nuclear power is commonly associated with base load electricity generation, nuclear plants have typically been designed for some degree of load following and other aspects of flexible power operations (FPO). French and German nuclear power plants have long been operated in a flexible manner to balance production and demand for grid stability through adjustments to electrical output and power ramping.

Growing public and private investment in advanced reactor development, demonstration, and commercialization presents a unique opportunity to apply lessons learned from the current fleet and to reimagine the role and value of nuclear energy systems to meet future societal energy demand while also adapting to changing market, policy, and regulatory environments.

1.2 Flexibility of the Current Nuclear Fleet

The ability of existing, largely Generation II, NPPs to operate flexibly to provide load following and frequency control services to power grids is solidly established in the global operating experience. This capability has been firmly embedded in contemporary design requirements for Generation III light water reactors; both the European Utility Requirements document (EUR) and the EPRI Utility Requirements Document (URD) elaborate end-user expectations of significant operational flexibility for large LWRs and, in the case of EPRI's latest URD revision, small modular LWRs (EPRI 2014b; EUR 2016). Table 1 depicts consensus requirements from utility owner-operators for minimum load following and frequency control capabilities of advanced LWR plants established in the 1990s (EPRI 1999).[1]

[1] Revision 8 of EPRI's URD is publicly available for zero-cost downloading.

Table 1 EPRI URD (Rev. 8) Load Following and Frequency Control Requirements for Advanced Light Water Reactors. Source: EPRI (1999)

Load Following	Frequency Control
<u>Load Cycle Profile</u> The plant shall be designed for a 24-hour load cycle with the following profile: starting at 100 percent power, power ramps down to 50 percent power in two hours, power remains at 50 percent for two to ten hours, and then ramps up to 100 percent in two hours. Power remains at 100 percent for the remainder of the 24-hour cycle.	<u>Control Profile</u> The plant shall be designed to operate in an automatic mode in response to grid frequency changes. In terms of power output modulation, the plant shall be capable of satisfying peak-to-peak power change demands of 10 percent of plant rating at 2 percent of plant rating per minute. Frequency control is to be provided while performing ramp power changes required for load following (see paragraph 3.4.1.1) as well as being provided within the power operating range of 50 to 100 percent.
<u>Duty Cycles</u> The plant shall be designed to permit the utilization of the load following capability during 90 percent of each fuel cycle throughout the entire design life of the plant.	<u>Duty Cycles</u> The plant shall be designed to permit the utilization of the frequency control capability throughout the operating life of the plant. Thirty-five peak-to-peak swings per day of operation shall be permissible.

EPRI started evaluating flexible operations for current NPPs based on the emerging demand in several U.S. electricity markets; a formal FPO program was established in 2015 based on expanding utility interest in and need for transitioning away from a base load operating regime. As a result of collaboration and target research on impacts and mitigation strategies, several NPP operators in the U.S. have developed FPO plans. The primary components of these plans are establishing protocol with the grid system operator and defining a plant “safe operating envelope”. This envelope is defined for a variety of phases in which the plant departs from full power operations. These phases and their implementation status are illustrated in Figure 1.

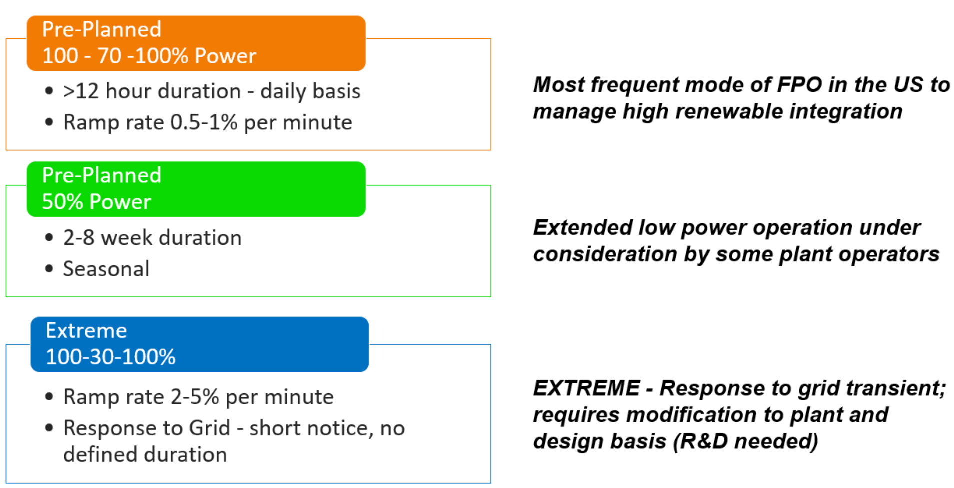

Figure 1 Categorization of Flexible Operations for Nuclear Power Plants in the United States by Ramping Requirements, Frequency, and Duration.

Source: EPRI. Used with permissions.

FPO of the global operating nuclear fleet can vary significantly between regions. In some countries, such as France and Germany, power ramping, rotational inertia, and other responses have been used extensively for load following and grid frequency control. France currently operates 56 reactors that can vary output between 20% and 100% power within 30 minutes, and provide automatic frequency controls (Morilhat 2019). While many U.S. NPPs have the capability to function in this manner, U.S. NRC 10CFR50.54(i) requires that all manipulation of the controls of an NPP must be performed by licensed operators, thus excluding control changes by grid signals without regulatory changes. Expanding interest in and development of a new generation of nuclear plant designs, including small modular light water reactors (LWR) and non-water-cooled technologies, presents a rare opportunity to rethink plant capabilities. This includes expanding the concept of flexibility to better utilize the unique attributes and capabilities of nuclear energy systems to meet future electricity and energy needs and respond to ever changing economic, market, and policy landscapes.

1.3 Relevance of an Expanded Flexibility Concept

Flexibility as a concept is not meaningful without adequate context and purpose, and an imprudent pursuit of excessive flexibility through design margins can be expected to drive unjustifiable cost increases and other negative consequences for commercial viability. Perhaps the greatest value is as a hedge against uncertainty. Advancements in competing technologies, world events, shifting policies, social acceptance, natural disasters, and other external factors have frequently disrupted energy forecasts and utility capacity expansion planning. The rapid deployment of hydraulic fracturing or "fracking" in the late 2000s led to a significant drop in natural gas prices and a dramatic reversal of generation forecasting for the U.S. power sector. Prior to 2008, capacity expansion modeling generally projected static or declining reliance on natural gas for electricity generation due to price variability, continued dominance of coal, and other assumptions (EPRI 2008). Instead, natural gas contributions increased from 1% of electricity generation in the U.S. in 2000, to over 20% in 2010; natural gas generation has continued to increase, accounting for 37% of U.S. electricity generation in 2018 (USBLS 2018; EIA 2019).

The potential for unexpected and disruptive changes to the energy landscape represents both a challenge and an important opportunity for advanced reactors if those technologies offer compelling enough attributes to overcome adoption risks. In addition to uncertainty, known future opportunities for new nuclear expansion (and competitors) will likely arise in the form of replacement generation capacity for retiring nuclear, fossil, and renewable assets and new generation to meet demand increases. Current global investment in energy infrastructure exceeds a trillion USD annually, and the International Energy Agency estimates this investment will need to more than double to meet demand growth while also meeting decarbonization goals (IEA 2017, 2019).

Policy or market incentives for decarbonization of the electricity sectors and the broader energy infrastructures are projected to favor substantial growth in new nuclear deployments for a range of scenarios (EPRI 2018). In the United States, a growing list of electric utilities have announced commitments to zero or low carbon generation by the year 2050 (Southern Alliance for Clean Energy 2019). And, as energy demands increase, the demand for nuclear capacity could double that of the current installed capacity if decarbonization goals are to be achieved (IEA/NEA 2015).

1.4 An Expanded Flexibility Paradigm

Construction of large advanced light water reactors (ALWR) continues around the world, and these new builds can be expected to operate through the end of the 21st century. Therefore, LWR technology will continue to represent a backbone of nuclear energy generation into the foreseeable future. However, surging interest in small modular LWRs, advanced non-light-water reactors, and megawatt-scale microreactors indicates a more diverse technology mix.[2] Moreover, higher temperature operation and other attributes signal a potential expanded application of nuclear technology to non-electrical missions and expansion beyond electricity markets. Together, this diverse collection of new nuclear designs brings potential owner-operators new benefits and opportunities through an expanded menu of physical characteristics and engineering options for:

- Inherent safety
- Robust, competitive, sustainable economics
- Scalable, dispatchable, energy-dense, non-emitting generation
- Diversified products and market access
- Secure fuel supply
- Flexible operation

Many of the key positive (and negative) attributes of reactor systems are driven by the properties of the choice of primary system coolant or working fluid, properties that drive economics, material performance, safety, and overall system complexity and cost. Figure 2 depicts the representative primary system pressures and temperature envelopes of existing and new nuclear plant designs: lead-cooled fast reactors (LFRs); sodium-cooled fast reactors (SFRs); molten salt reactors (MSRs); high-temperature gas-cooled reactors (HTGRs); gas-cooled fast reactors (GFRs); supercritical water reactors (SCWRs); and LWRs. Boiling water reactors (BWRs) and pressurized water reactors (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 practical access to dry cooling, more advanced power conversion cycles (e.g., supercritical-CO_2 Brayton cycles), and non-electric markets. Lower operating pressures should yield a parallel set of benefits, including less costly primary system components and less energetic accident scenarios resulting in reduction or elimination of off-site consequences.

[2] In this chapter, "advanced reactor" is invoked as a general term to encompass the many categories of advanced fission designs. These include the Generation IV International Forum GEN IV designs, light water small modular reactors (SMRs), and so-called microreactors. EPRI considers advanced reactors to be technologies beyond current Generation III/III+ designs, with most employing coolants and/or working fluids other than water.

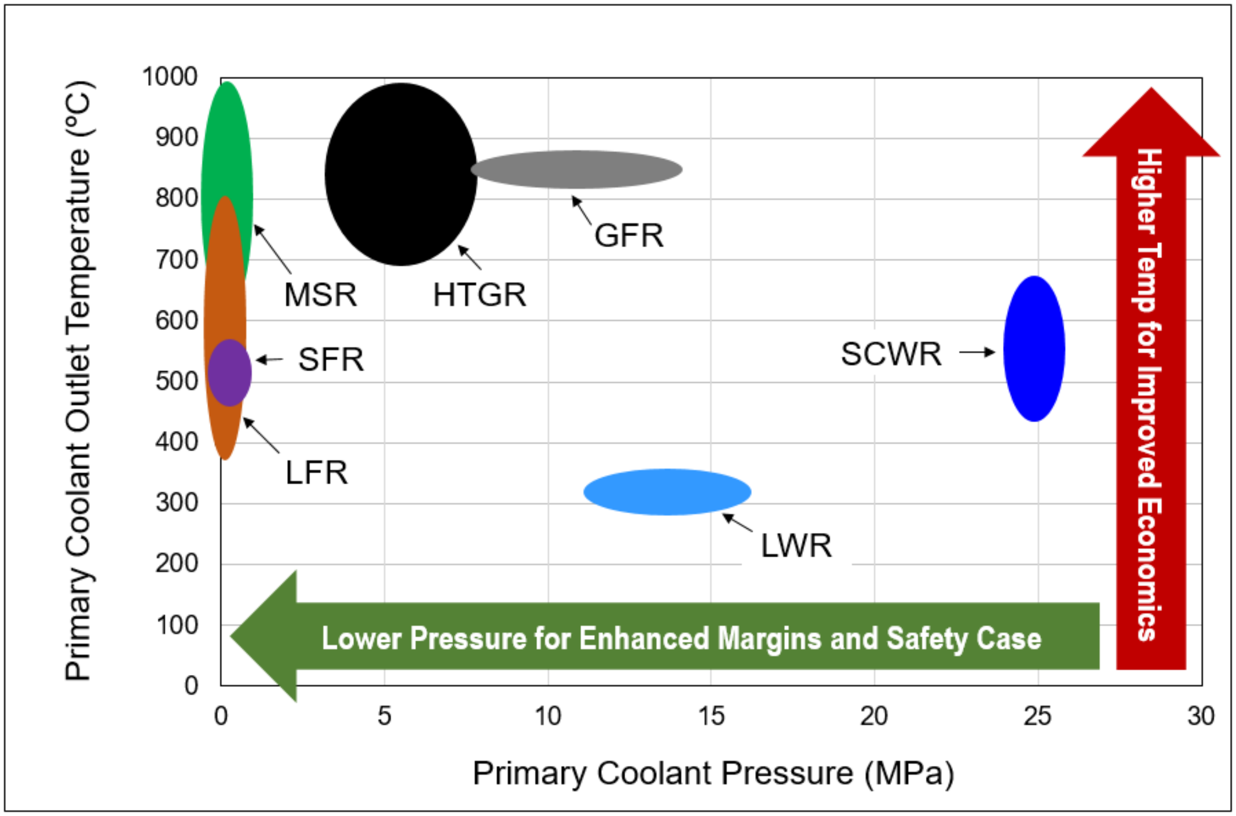

Figure 2 Primary coolant outlet temperature vs. pressure for current and advanced reactors.

Source: EPRI. Used with permissions.

The expanded opportunities and motivations for design and deployment of advanced nuclear energy systems suggest a flexibility that goes beyond the traditional definition applied to operation of existing generation assets. Accordingly, EPRI has developed an expanded concept of flexibility and associated evaluation criteria to better capture key attributes and applications of advanced reactor technology, including light water small modular reactors (SMRs) and non-LWRs (Sowder et al. 2016; EPRI 2017).

Based on elicitation of input from the advanced reactor community through direct engagements and other related EPRI R&D activities (EPRI 2014c), three broad flexibility categories or criteria are proposed for nuclear plant technology moving forward:

1. Operational Flexibility - the ability of a nuclear energy system to be operated under a range of conditions through maneuverability (e.g., load following), fuel flexibility, compatibility with hybrid power systems and polygeneration (see below), and remote/island operation.

2. Deployment Flexibility - the ability of a nuclear energy system to be licensed, financed, sited, and built under a wide range of external conditions through ease of scaling and siting, including the application of modular manufacturing and construction methods.

3. Product Flexibility - the ability of a nuclear energy system to fulfill more than one mission though product diversity (i.e., polygeneration).

These three broad attributes were further refined and elaborated via multiple iterations from two targeted workshops and industry feedback. They are presented in Table 2 with more detailed descriptions to follow.

Table 2 EPRI expanded framework for describing flexibility of nuclear energy systems. Adapted from EPRI (2017).

Attribute	Sub-Attribute	Benefits
Operational Flexibility	Maneuverability	Load following
	Compatibility with Hybrid Energy Systems and Polygeneration	Economic operation with increasing penetration of intermittent generation, alternative missions
	Diversified Fuel Use	Economics and security of fuel supply
	Island Operation	System resiliency, remote power, micro-grid, emergency power applications
Deployment Flexibility	Scalability	Ability to deploy at scale needed
	Siting	Ability to deploy where needed
	Constructability	Ability to deploy on schedule and on budget
Product Flexibility	Electricity	Reliable, dispatchable power supply
	Process Heat	Reliable, dispatchable process heat supply
	Radioisotopes	Unique or high demand isotopes supply

1.4.1 Operational Flexibility

Maneuverability: The ability of the reactor and balance of plant systems (reactor and power conversion) to change power level and corresponding outputs in terms of extent and rate to match changing operational requirements and external conditions, including electrical load following.

Flexible maneuverability allows a plant to operate in a variety of ways. The plant can continue to perform base load generation duties but can additionally perform primary and secondary frequency control as well as operating in electrical load-following mode. Producing base loads is the preferred mode for most NPPs due to the simplicity and efficiency, but they can adjust electrical output on hourly scales to accommodate changing grid requirements. Independent system operators can direct plants to restore and maintain grid frequency when a plant operates in frequency control mode. When load-following, plants can move control rods, modify boron concentrations, change various internal mechanisms on the nuclear side, or manipulate operations on the balance-of-plant side to allow for adjusting plant electric output in order to meet grid energy demand and stability requirements.

Compatibility with Hybrid Technologies and Polygeneration: The ability of a nuclear energy system to operate in concert with other energy sources to provide two or more products and/or services.

These systems may support thermal energy storage, load-following missions, or industrial processes that produce commodities. As renewables continue to penetrate the market and introduce large periods of variable generation, thermal energy stored by NPPs can smooth supply and demand profiles. The stored heat can be used in combined cycle plants to meet peak demands when needed. In principle, when electricity prices are driven low during hours of peak solar generation a polygenerating NPP could divert some quantity of energy generated to the production of hydrogen, ammonia, or various other storable industrial commodities.

Diversified Fuel Use: The ability to operate a nuclear reactor system using a variety of fuel designs, fuel materials, and fuel systems.

A system capable of functioning with various fuel designs, materials, and configurations could be capable of functioning in larger operational envelopes while maintaining similar performance and safety margins to current standards (NEA 2018). Many currently pursued fuel materials for enhancing accident tolerance may function better in the gas and salt coolant systems used in many advanced reactors. Several such systems can be designed to operate using varying fuel types and fuel cycles based on the energy needs that are anticipated.

Island Operation: The ability to operate in isolation from local, regional or national electricity distribution networks either on a routine or exceptional basis.

There are two functional modes to island operation. The first is stand-alone generation, where the production is independent from any grid; the second is micro-grid support and parallel grid connection so as to support a system in the result of a widespread power outage (Tjellander 2008). The modular reactors in Gen IV are well designed for island operation based on multiple design features, such as long core lives, minimized maintenance, and simplified operations.

1.4.2 Deployment Flexibility

Scalability of System: Ability of nuclear reactors to be scaled to match energy demand and to meet other local and regional requirements.

Scaling a system can be achieved in a variety of ways, including power uprates to existing generation, additional of capacity through modular deployment, and adding variable capacity through installation of differing power level units. Power uprates are one of the current methods used to scale a nuclear system. By optimizing thermal hydraulics, core neutronics, and fuel design, the U.S. has been able to increase generation capacity by approximately 7 GWe through power uprates alone since 1977 (USNRC 2014). Incremental capacity increase is possible in plants utilizing multiple SMRs, which can be delivered to the site fully manufactured as energy demand in a region grows. The inherent scalability of a technology may also facilitate development of designs to cover a range of power outputs such that deployment of individual units can be better tailored to power demand and grid connection limits.

Compatibility with Siting: The ability to license, construct, and operate a nuclear reactor where desired.

There are a multitude of requirements to site a NPP, from seismic activity and aesthetics (USNRC 1998) to land use and cooling water presence (Belles et al. 2013). Many Gen IV reactors require considerably less land than current large scale LWRs, with some reports indicating 1-2 orders of magnitude less (NEI 2015). This would enable the fulfillment of missions for which current LWRs are incapable, due to necessary proximity to consumers.

Constructability: The relative ease with which nuclear systems can be built on schedule and budget.

One of the greatest benefits to constructability of advanced reactors is in the area of modularity. When plant components can be designed and manufactured before being transported to the site for installation, cost per component will be reduced. The standardization of parts should improve the quality, as well as reduce the rework and reinspection needed at times when redesign is necessary.

1.4.3 Product Flexibility

Electricity Production: The ability of a nuclear reactor to efficiently convert thermal power to electricity. Thermal conversion efficiency generally increases with reactor outlet temperature.

Electricity is the dominant product from commercial nuclear plants, and electricity generation remains the dominant reference business case for many advanced reactor designs. As discussed previously, electricity can be generated in various operating modes including continuous base load generation and load-following.

Industrial Process Heat Production: The ability of a nuclear system to produce process heat of sufficient quality for industrial use.

Process heat represents a large potential revenue source for advanced nuclear reactors. With some designs capable of output temperatures above 550 °C, high quality heat can be applied to a variety of applications including shale oil recovery, high-temperature steam electrolysis, chemical production, and water desalination (INL 2011; IAEA, 2012, 2018; Forsberg 2013). The cost associated with producing these products is often dominated by the energy consumed, so supplying high quality heat with high availability factors represents an opportunity to pursue new and potentially more lucrative markets. However, direct heat markets are limited to end-users physically located within the range over which heat can be transferred economically and typically require very high availability factors.

Radioisotope Production: The ability of a nuclear system to be utilized for the production of desirable radioisotopes.

Commercial power reactors generally do not produce radioisotopes, although notable exceptions do exist. Instead, most radioisotopes for medical, research, and industrial uses are produced in research reactors and accelerators. Critical reactors offer advantages over other isotope production methods, such as accelerator driven systems, including larger irradiation volumes capable of hosting multiple targets and producing a larger range of isotopes. New features and attributes of advanced reactors, for example liquid-fueled concepts, offer new opportunities and competitive benefits for co-production of radioisotope products in parallel with power and/or heat generation missions.

1.5 Valuing Flexibility

Many advanced reactors are distinguished by higher outlet temperatures, introducing the possibility of more efficient forms of thermal utilization. The cogeneration of electricity with hydrogen, for instance, would allow a plant to generate electricity when prices are high, but to produce and store hydrogen when prices are low or negative. Instead of flexibly varying power output to reduce electricity generation, an advanced reactor would flexibly vary the proportion of power output creating electricity and generate more hydrogen when it is economically preferable. The sensitivity of nuclear capacity expansion by 2050 in the United States is illustrated in Figure 3 for a range of nuclear capital costs and subject to policy and non-electric revenue scenarios (EPRI 2018). These scenarios include: additional revenue of \$5 and \$15 per MWh from sources beyond electricity sales (in green); a \$15 per ton CO_2 tax (in grey); a national renewable portfolio standard (RPS) policy that includes new nuclear but not existing NPPs (in black), and the reference status quo scenario (in blue).

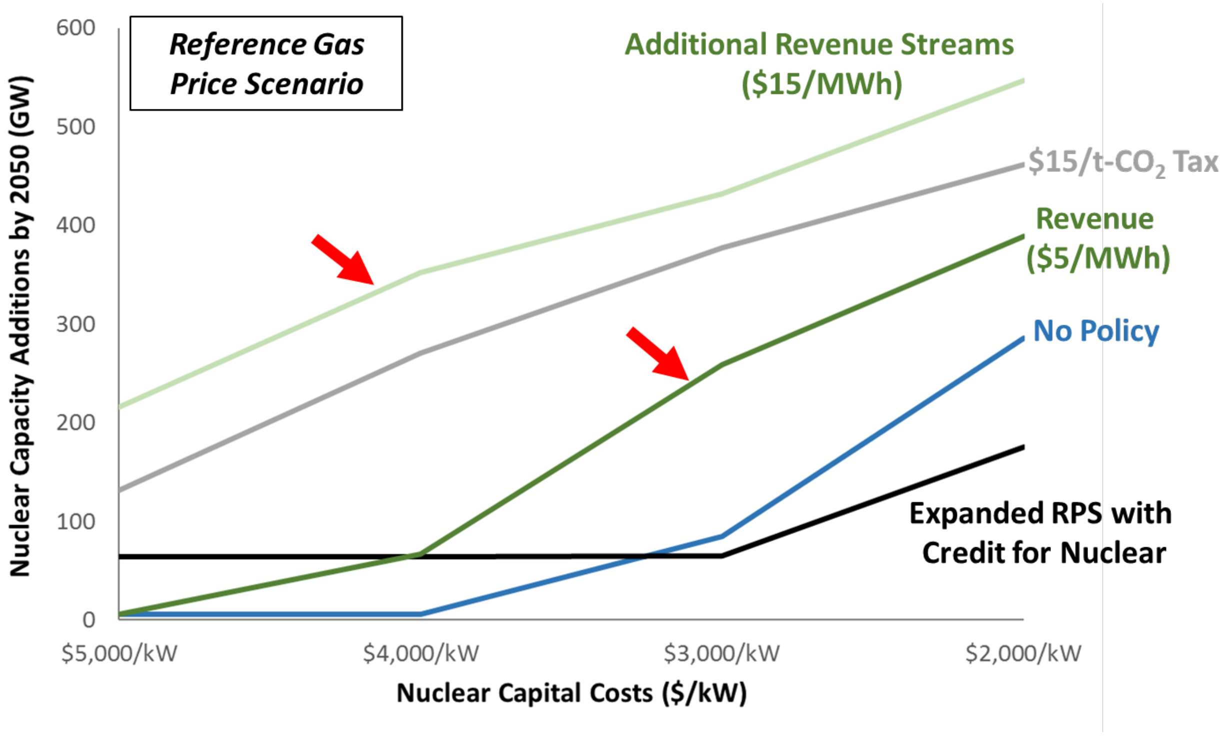

Figure 3 Flexibility and economics go hand-in-hand. Improved nuclear competitiveness comes with increased non-electric revenues in addition to other policy drivers. Adapted from EPRI (2018).

Source: EPRI. Used with permissions.

The product flexibility that can be innate to advanced reactors could allow this additional revenue stream to be chosen based on a variety of factors, including site proximity to industry or regional electrical demands. Improved constructability offered by advanced nuclear system designs has the potential to reduce capital costs, which could in turn enable the increased deployment of advanced reactors for supporting various industrial heat needs that would not be economical with current overnight costs. The potential for island operation built into a design allows for a variety of missions from powering military bases to heating remote communities, allowing one reactor design to serve multiple missions.

1.6 Implementing Flexibility in Advanced Reactors

As designs of the next generation reactors mature, are licensed, and are procured by utilities and other end-users, key attributes, primarily applications, and owner business cases are likely to evolve as future changes to market and policy environments unfold. In preparation for changing customers and markets for advanced nuclear technologies, EPRI is developing a new owner-operator requirements framework to stabilize definitions, inform stakeholders, enhance and accelerate alignment of end-user needs with design attributes, and facilitate engagement with regulators. EPRI's Advanced Reactor Owner-Operator Requirements Guide (ORG) seeks to provide a similar function the established examples of the URD and EUR while reflecting and serving the contemporary needs of an expanded and diverse marketplace of advanced reactor technologies and missions (EPRI 2019). Now in its second revision, the ORG represents an ongoing effort to provide a high-level, technology and mission inclusive framework. A key theme integrated into the ORG is the expanded flexibility paradigm as it relates to all aspects of plant design, deployment, and operation.

The case for practical implementation of flexibility for advanced reactors is increasing in relevance and strength. The U.S. NRC is considering the modification of emergency planning zones requirements based on the enhanced safety case and margins offered by light water SMR designs (USNRC 2020). Relaxation of siting restrictions could, for example, enable plant deployment closer to end users and communities. Similarly, increasing industry focus on the development and application of new construction methods and technologies, such as steel-concrete composite construction (SC), promises to provide the practical means to implement construction flexibility for reduced construction duration and more predictable construction schedules.

1.7 Summary

Flexibility is a well-established and recognized feature applicable to existing reactor technology in the context of flexible power operation—a term generally used to describe any operational mode in which the plant electric power output is varied in response to regional electrical grid demands. Plants in France and Germany have long been relied on for load following and frequency control to support grid stability. As the penetration of variable generation, grid congestion, and other grid and market pressures continue to grow in the United States, utilities are transitioning their nuclear units from base load to flexible operation.

EPRI is taking the lessons and operation experience gained from the flexible operation of current nuclear operators worldwide to define and elaborate an expanded concept of flexibility to inform owner-operator requirements and design attributes of a new generation of advanced fission reactors. EPRI sees expanded flexibility criteria as a useful framework for describing and understanding compelling features and capabilities of advanced reactor technologies.

EPRI's expanded flexibility paradigm is built on and expanded through several subcategories, namely operational flexibility, deployment flexibility, and product flexibility. While the current generation of nuclear reactors may be able to take advantage of several aspects of this expanded flexibility, the "blank slate" opportunity presented by the design of a wide assortment of new generation smaller, modular reactors affords an unique opportunity to integrate greater flexibility into the design, siting, construction, and operation of new plants.

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