

LWR Fleet Uprate and Capacity Expansion Opportunities



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55 East Monroe Street
Chicago, IL 60603-5780 USA
312-269-2000
www.sargentlundy.com



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ISSUE SUMMARY AND APPROVAL PAGE

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Contributors

Prepared by:

Name	Signature	Date
Henry Fidlow	<i>Henry Fidlow</i>	02/13/2026

Reviewed by:

Name	Signature	Date
Thomas Bartoski	<i>Thomas Bartoski</i>	02/13/2026
David Gardiner	<i>David Gardiner</i>	02/13/2026
Steven Malak	<i>Steven Malak</i>	02/13/2026
Allen Williams	<i>Allen Williams</i>	02/13/2026

Approved by:

Alan J. Wilson

02/13/2026

Alan J. Wilson

Date

Sr. Vice President

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ACRONYMS AND ABBREVIATIONS

Acronym/Abbreviation	Definition Clarification
A/E	Architect-engineering
AI	Artificial intelligence
APRM	Average Power Range Monitoring
ASME	American Society of Mechanical Engineers
ATWS	Anticipated transient without scram
BOP	Balance of plant
BWR	Boiling water reactor
CARV	Cross Around Relief Valve
CLTP	Current Licensed Thermal Power
DVR	Data Validation and Reconciliation
ECCS	Emergency Core Cooling Systems
EHC	Digital Electro-hydraulic Control
EO	Executive Order
EPU	Extended Power Uprate
EPU+	Extended Power Uprate Plus
EQ	Equipment Qualification
FERC	Federal Energy Regulatory Commission
FW	Feedwater
GEZIP	General Electric Zinc Injection Passivation
GOES	Grain Oriented Electrical Steel
GSU	Generator Step-up Transformer
GWe	Gigawatt-electric
HD	Heater Drain
HP	High-pressure
INPO	Institute of Nuclear Power Operations
LAR	License Amendment Request
LEFM	Leading Edge Flow Meter
LEU	Low Enriched Uranium
LEU+	Low Enriched Uranium Plus
LP	Low-pressure
LWR	Light water reactor
MELLLA+	Maximum Extended Load Line Limit Analysis Plus
MOV	Motor operated valve
MS	Main Steam
MSCV	Main Steam Control Valve
MSIV	Main Steam Isolation Valve
MSR	Moisture separator reheater
MUR	Measurement Uncertainty Recapture

Acronym/Abbreviation	Definition Clarification
MWe	Megawatt-electric
MWt	Megawatt-thermal
NMS	Neutron Monitoring System
NRC	United States Nuclear Regulatory Commission
NSSS	Nuclear steam supply system
O&M	Operation and maintenance
OE	Operating experience
OEM	Original equipment manufacturer
OLTP	Original Licensed Thermal Power
PUC	Public Utilities Commission
PWR	Pressurized water reactor
RCIC	Reactor Core Isolation Cooling
RFP	Reactor Feed Pump
RHR	Residual Heat Removal
RHRSW	Residual Heat Removal Service Water
RTO	Regional Transmission Organization
RWCU	Reactor Water Cleanup System
SGTS	Standby Gas Treatment System
SLC	Standby Liquid Control
SLRA	Subsequent License Renewal Applications
SPU	Stretch Power Uprate
UHS	Ultimate Heat Sink
U.S.	United States

EXECUTIVE SUMMARY

Recent Executive Orders have called for the U.S. nuclear fleet to prioritize capacity expansion to support grid stability and demand growth. These directives call for five gigawatts (5 GWe) and 300 gigawatts (300 GWe) of nuclear capacity additions by 2030 and 2050, respectively. While new nuclear reactors are planned to account for a majority of the long-term target, thermal and efficiency power uprates can help meet this growth target near-term.

The existing U.S. nuclear fleet has realized approximately eight gigawatts (8 GWe) in added licensed capacity through thermal power uprates. Of this, half of the incremental capacity has been driven by extended power uprates (EPUs), with the remainder comprised of smaller stretch power uprates (SPUs) and measurement uncertainty recapture (MUR) uprates. Despite the 172 Nuclear Regulatory Commission (NRC) approved uprates, there is still significant margin for existing nuclear power plants to gain additional gigawatts through new thermal power uprates. Performance modifications can further increase electrical output by improving thermal-to-electric conversion efficiencies.

This report investigates the history of power uprates in the United States and identifies potential areas for further uprate capacity. Power uprates are complex, multi-year integrated projects that must navigate technical, operational, regulatory, supply chain, and financial challenges. These challenges are discussed in detail herein, alongside potential mitigating strategies to increase investor confidence and project success factor. Included in this discussion is a framework for evaluating optimal power uprate level, considering the plant design and licensing basis, uprate history, margin assessment, and market conditions.

The supply chain is a critical path in any power uprate project. Supplier interviews are conducted as part of this effort to gather perspective on lead times, technical/market challenges, and areas for incentivization to reduce cost and accelerate implementation timelines. Key long lead items for uprates include steam dryers, main turbines, main generators, generator step-up (GSU) transformers, moisture separator reheaters (MSRs), and feedwater heaters. Recent macroeconomic uncertainty, poor demand forecasting, limited standardization, and an atrophied domestic nuclear supply chain have exacerbated challenges for both suppliers and nuclear power plant owner-operators. Improved coordination between utilities and suppliers, market certainty, government support for domestic suppliers, clarification of code requirements for nuclear-grade components, and greater design standardization can all help address the supply chain challenge.

Power uprate projects are an essential solution to help meet the Administration's 2030 nuclear capacity expansion target. Nevertheless, they also provide an invaluable opportunity to kickstart the nuclear supply chain and workforce as the industry transitions toward new reactors.

1. RESEARCH INTRODUCTION AND OBJECTIVES

1.1. BACKGROUND AND MOTIVATION

Since 1990, United States (U.S.) nuclear energy capacity has remained largely stagnant at around 100 GWe [3]. While fleet capacity factor has significantly improved from ~60% in the late 1980s to ~93% today [4], further improvements are expected to be rather small. From a capacity perspective, market competition and high capital investment requirements have stagnated new nuclear construction over this same timeframe.

Despite the challenges to developing new nuclear capacity, recent years have seen multiple positive tailwinds for the industry. Increasing renewable penetration and fossil fuel power plant retirements have increased grid supply-side variability, emphasizing the importance of baseload generation such as nuclear. Furthermore, projected load growth through the rapid adoption of artificial intelligence (AI) has provided a new market particularly well-suited to the nuclear power industry. The current presidential administration has established several Executive Orders calling for increased nuclear power production as both a short term and long term solution to domestic energy demands.

Executive Order 14302 Section 4(a) states “the Department of Energy shall prioritize work with the nuclear energy industry to facilitate 5 gigawatts of power uprates to existing nuclear reactors and have 10 new large reactors with complete designs under construction by 2030” [1]. Executive order 14300 Section 2(c) stipulates the U.S. “facilitate the expansion of American nuclear energy capacity from approximately 100 GW in 2024 to 400 GW by 2050” [2].

From these strategic goals, the need for increased nuclear power production is readily apparent. In the short term, maximizing capacity and capacity factor is essential to quickly meet load growth demands. Beyond the next five (5) years, large-scale design and buildout of new reactors will enable further nuclear power adoption. Throughout this energy transition, maintaining capacity and reliability of the existing U.S. light water reactor (LWR) fleet will be essential to support the grid and health of the nuclear industry.

1.2. OBJECTIVES

The purpose of this study is to outline the opportunities for capacity expansion and acceleration for existing U.S. nuclear power plant assets, highlighting challenges foreseen with power uprates, suggested areas for future research, and incentives to maximize near-term capacity growth. A framework for uprate project planning is developed to support first-order project cost estimation and uprate optimization. Supply chain constraints are explored in detail for critical uprate equipment to identify strategic planning, demand certainty, and supply-side relief focus areas that will alleviate potential procurement bottlenecks.

1.3. CAPACITY EXPANSION OPPORTUNITIES FOR LWR FLEET

Capacity expansion applies to both existing and new assets. Existing assets, including both operating and non-operating reactors, can realize increased electricity production via:

- Thermal Upgrades: Increasing the thermal power output (MWt) of operating nuclear power plants through plant modifications that enable increased licensed reactor power.
- Efficiency Upgrades: Increasing the electrical power output (MWe) of operating nuclear power plants through plant modifications that improve equipment performance and plant efficiency.
- Capacity Factor Optimization: Increasing the capacity factor of operating nuclear power plants by reducing outage durations and minimizing the occurrence of events that lead to lost generation, SCRAMs, and unplanned outages.
- Plant Restarts: Bringing shutdown nuclear power plants back into operation.

Future capacity expansion is associated with the development of new assets including both large reactors and small modular reactors. While this will provide greater growth potential in the long run, the planning of new nuclear assets is not the focus of this investigation.

1.4. POWER UPRATE TYPES

Historically, there have been three (3) main types of thermal power uprates implemented for light-water reactors: measurement uncertainty recapture (MUR) power uprate, stretch power uprate (SPU), and extended power uprate (EPU) [8]. Beyond these levels, there has been interest in even greater, novel EPU+ uprates. Below is a summary of the uprate levels, impacts, timeline, and cost.

1.4.1. Measurement Uncertainty Recapture (MUR)

10 CFR 50 Appendix K stipulates "... it must be assumed that the reactor has been operating continuously at a power level at least 1.02 times the licensed power level (to allow for instrumentation error)". Through enhanced methods of measuring reactor power, MUR power uprates allow utilities to reclaim portions of this uncertainty margin. These uprates, typically between 1-2%, are facilitated through the use of feedwater flow measurement devices with improved precision and accuracy. These small uprates do not require significant equipment upgrades and are therefore relatively quick (2 to 3 year project lifecycle) and inexpensive (~\$1,400/kW) to implement [16].

1.4.2. Stretch Power Uprate (SPU)

Nuclear power plants are designed with margin between their operational limit and the reactor vendor's analyzed design limit for the plant. SPUs recapture this design margin, ideally with minimal equipment modifications through changes in instrument setpoints. In reality, significant modifications are often required. The level of power increase is plant specific but normally hovers around 105% of original licensed thermal power (OLTP) for boiling water reactors (BWRs) and 107% of OLTP for pressurized water reactors (PWRs). These uprates typically take 5-7 years from project inception to implementation, and cost >\$3,000/kW [16].

1.4.3. Extended Power Uprate (EPU)

To enable greater EPUs beyond 7% up to 20%, average core power density must increase. Core design changes may include adjusted fuel loading patterns, burnable poison distributions, and new fuel designs, among other methods. These changes result in increased core flow and steam flow in the balance of plant (BOP). To accommodate these flow increases, significant modifications are typically required for major BOP equipment such as the turbine-generator, condensate and feedwater pumps, and large transformers. While BWR EPUs generally require steam dryer replacement (non-safety related), large Nuclear Steam Supply System (NSSS) modifications such as steam generator replacements (safety related) are often the “pinch-point” limiting larger EPU uprates for PWRs. EPUs generally have similar timeframes and normalized costs as SPUs [16].

For BWRs, licensing topical report GE NEDO-32424 [15] was developed to provide generic guidance for both utilities and the NRC to support EPUs up to 20% above OLTP without major NSSS hardware modifications. Similar generic guidance does not exist for PWRs, which are often limited to EPUs closer to 10% above OLTP (as detailed in Section 1.5).

1.4.4. Extended Power Uprate Plus (EPU+)

The BWR fleet has largely realized +20% EPU uprates by leveraging existing design margin and generic guidance per the NRC accepted licensing topical report. The PWR fleet does not have similar generic EPU guidance; site-specific plant analyses for PWRs have typically resulted in smaller uprates which avoid major NSSS modifications that were not shown to be financially justifiable. In this changing regulatory and market environment, these bounding limits demand reevaluation.

Both BWR and PWR reactor vendors have indicated potential to perform uprates beyond current historically-achieved levels. An EPU+ uprate for a BWR would be upwards of 30% above OLTP. An EPU+ uprate for a PWR would be approximately 20% above OLTP. These uprates would be achieved through a combination of regulatory change for safety analysis (e.g., time-at-temperature, risk-informed, etc.), change in the fuel/core design (e.g. accident tolerant fuel), and change in the approach for limits by the NSSS vendors from their current stance on power uprate limits. These EPU+ uprates would generally result in increased scope of modification for BOP and NSSS systems.

1.5. HISTORY OF THERMAL POWER UPRATES IN THE UNITED STATES

There have been 172 NRC approved power uprates, totaling 24,146 MWt (approximately 8 GWe) [5].

Table 1-1 summarizes the breakdown of historical power uprates by type. While EPUs only account for ~20% of all historical uprates, they have yielded approximately half of the total power increase for uprates.

Table 1-1. Historical Power Uprates in the United States

Uprate Type	# of Uprates	Thermal Power Increase (MWt)	Electrical Power Increase (MWe)*
MUR	73	3,456	1,151
SPU	65	8,488	2,827
EPU	34	12,203	4,064

* Electrical power is based on an assumed 33.3% thermal-to-electric conversion efficiency.

Market pressures in recent years have nearly eliminated power uprates. Notwithstanding a handful of recent MURs, there has not been an SPU or EPU application approved by the NRC since 2017 [5]. While there are currently no pending power uprate applications [7], the changing political and market state has resulted in several dozen uprate applications anticipated by 2030, as illustrated in Table 1-2.

Table 1-2. NRC Expected Power Uprate Applications Through 2030 [6]

Calendar Year	Total Power Uprates Expected	Measurement Uncertainty Recapture Power Uprates	Stretch Power Uprates	Extended Power Uprates	Megawatts Thermal	Approximate Megawatts Electric
2026	3	1	0	2	1,075	355
2027	16	7	2	7	2,589	854
2028	8	0	0	8	2,281	753
2029	0	0	0	0	0	0
2030	3	2	0	1	554	183
TOTAL	30	10	2	18	6,495	2,143

Across the current nuclear operating fleet, there have been some stark differences between BWR and PWR uprates. On average, the BWR fleet is operating at 114% of OLTP, whereas the PWR fleet is operating closer to 105% of OLTP. This is largely attributed to the generic BWR EPU guidance, which has provided a degree of standardization to 120% of OLTP.

While power uprate feasibility studies are unit-specific, it can be helpful to assess historical maximum power uprates collectively for different NSSS type to approximate margin availability under the current paradigm. This reinforces the notion that the entire BWR fleet should be able to realize combined uprate levels of 120% of OLTP or greater, whereas the PWR fleet has more restrictive, varied pinch points challenging 20% uprates.

Figure 1-1 illustrates current operating licensed power levels as a percentage above OLTP for different reactor designs. Peach Bottom 2 & 3 have been able to increase licensed reactor power to nearly 122% OLTP through the implementation of an EPU with MUR. Meanwhile, only a small portion of the PWR fleet has been able to implement EPUs beyond 110% OLTP. This stems from a variety of factors including plant specific evaluations and margin-driven cost limitations for large modifications such as steam generator replacement.

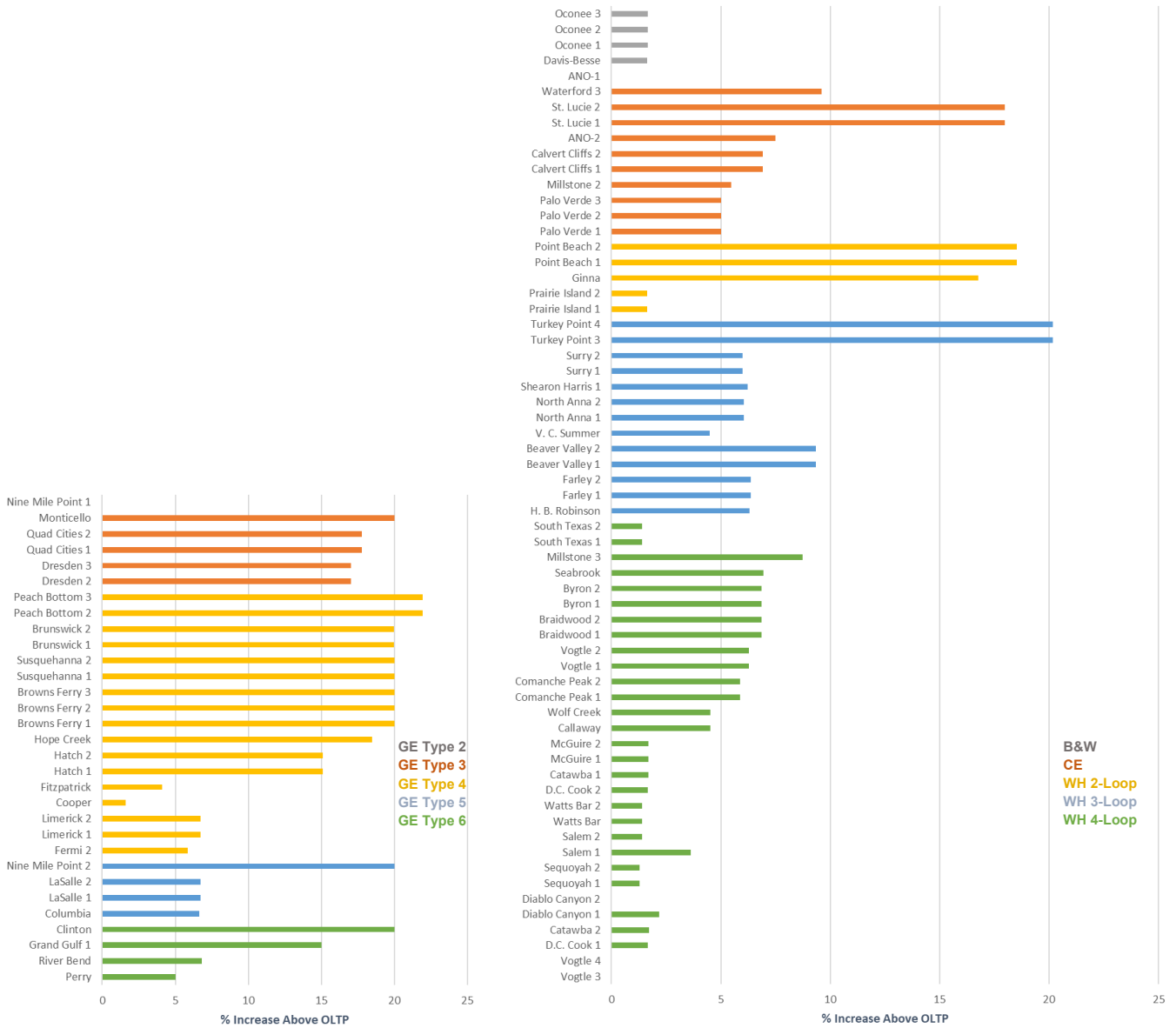


Figure 1-1. Current Power Uprate % by BWR (left) and PWR (right) Unit

Despite the historical challenge of large PWR EPU uprates, a number of PWR units have not implemented more than an MUR, hence significant capacity expansion opportunities remain on the PWR side through SPU and EPU uprates. Implementing these changes would enable the PWR fleet to reach an average uprate level of approximately 110% OLTP under present methods.

Figure 1-2 shows current (blue) and historical margin (yellow) for each unit as a percentage above OLTP.

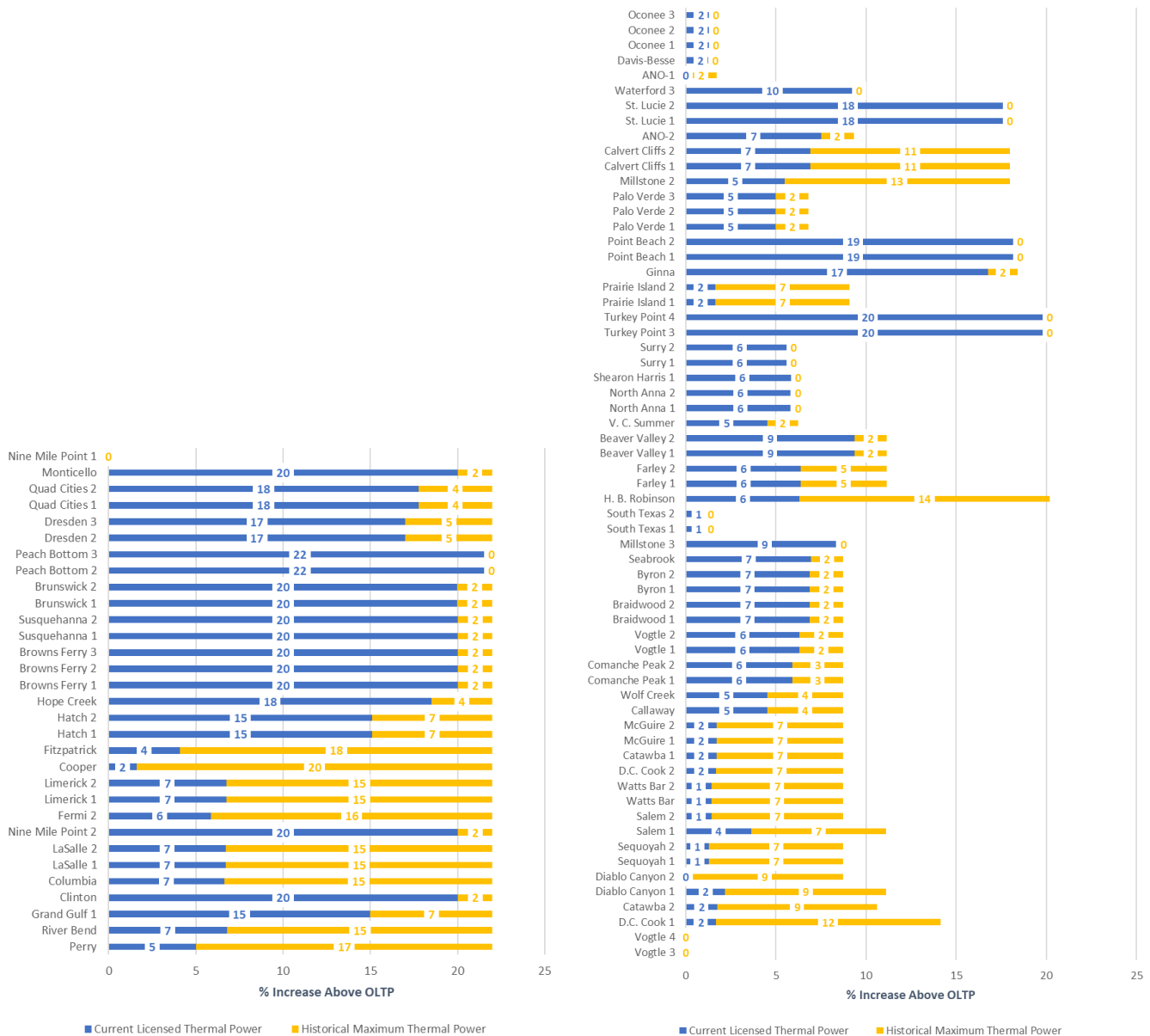


Figure 1-2. Current and Historical Maximum Power Uprate % by BWR (left) and PWR (right) Unit

There is approximately 6,000 MWt historically available within the BWR fleet, and 7,000 MWt historically available within the PWR fleet, yielding a combined potential for 13,000 MWt, or over 4 GWe.

Figure 1-3 illustrates the historical margin on an MWt basis to provide improved clarity on the magnitude of uprate margin available.

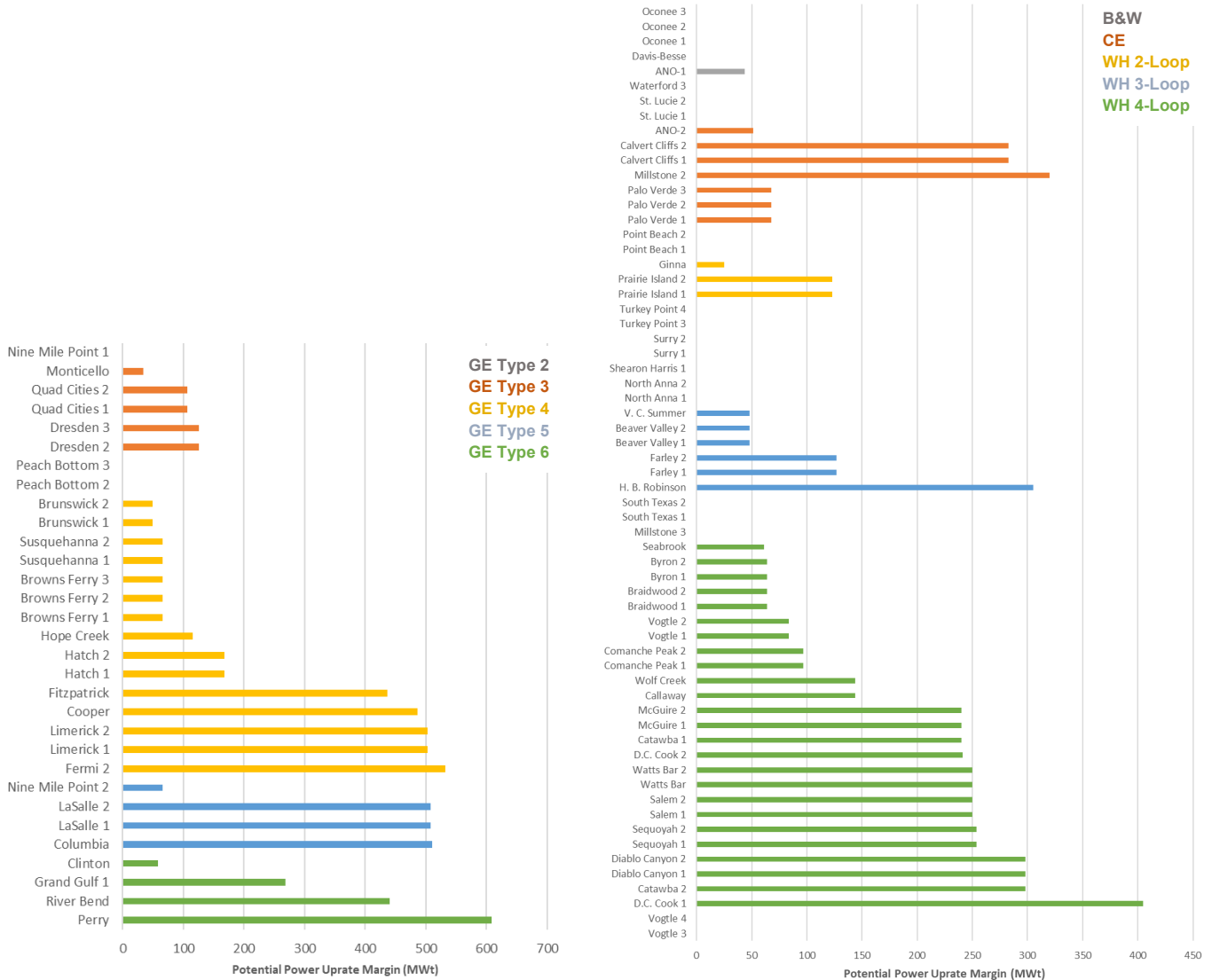


Figure 1-3. Potential Power Uprate Margin (MWt) by BWR (left) and PWR (right) Unit Based on Historical Uprates

Thermal power uprates alone do not paint the full picture for capacity expansion of operating power plants. BOP equipment replacements can also pave the way to improved thermal-to-electric efficiencies, allowing for increased electrical power output. The major opportunity here is turbine replacements; through longer, modernized 3-dimensional turbine blade designs, turbine performance can be significantly improved. Other BOP enhancements include replacement moisture separator reheaters (MSRs), feedwater heaters, and condenser tubes. Combined, these modifications can further increase electrical output upwards of 50 MWe per unit.

2. POWER UPRATE PROJECT PLANNING

There is a wealth of uprate industry knowledge through the 172 approved and implemented projects. Various design and implementation guides [10, 11, 12, 13] have been developed to support new uprate projects. While past knowledge should continue to be leveraged moving forward, rapid changes in the U.S. energy landscape coupled with opportunities for regulatory modernization and enhanced government support demand a reexamination of fleet-wide power uprate potential through updated methods.

This section explores the present challenges to larger uprate projects and faster implementation. Quantifiable evaluation criteria are developed from these challenges to inform a simplified uprate project planning framework that can be used to support uprate project selection optimization and cost prediction.

2.1. ADDRESSING POWER UPRATE CHALLENGES

Large thermal power uprate projects in the SPU and EPU domain are highly involved, with numerous system evaluations and plant modifications. Planning and implementation of these projects must effectively navigate technical/design challenges, operational factors, regulatory compliance, supply chain bottlenecks, and market conditions in order to successfully meet project cost and schedule. These factors often restrict the size of the power uprate projects pursued. The following discussion details some of these challenges, and methods to help alleviate constraints on project scope and timeline.

2.1.1. Technical/Design

On the technical front, development of a cross-functional design capturing the entire scope of impact for a large power uprate project poses a challenge to the timely development of design and licensing documentation. Initial feasibility must effectively assess equipment margins while considering the business case to define the most cost-effective uprate to perform. Sufficient depth of analysis in the early stages of a project is essential to clearly and correctly define plant impacts before any detailed system assessments and task reports can be developed. Effective collaboration between design organizations, reactor and equipment vendors, and plant engineering is required during detailed design to ensure the rapid transfer of input data to inform modification and LAR development. All together, these complex interfaces coupled with site-specific design facets present a significant technical challenge to the overall timeline for implementation.

When it comes to implementing larger uprates, workforce development and a modernized regulatory framework present major opportunities for improved design and integration. With over two-dozen expected uprate projects in the next few years, reactor vendors, site personnel, OEMs, and A/Es have significant opportunity to leverage learning effects and knowledge transfer to optimize designs. At the same time, continuing materials research for plant operating life extensions, improved fuels for greater power generation, and enhanced analysis methods can facilitate larger uprates if coupled with regulatory support.

A variety of computational programs are utilized to support the development of detailed design packages and uprate task reports. Appendix A highlights some of the software packages used to develop heat balances, thermal-hydraulic models, and probabilistic risk assessments among other uprate analyses. With the advent of new AI use cases and other innovative technologies, further design enhancements can be realized to address some of the complex design and technical challenges for power uprates.

2.1.2. Operational

Any large, system-integrated project presents operational risks and challenges. At the root of power uprate projects are impacts associated with tightened plant and equipment margins. Higher temperatures, pressures, and flow rates generally contribute to accelerated degradation, which must be closely monitored through inspection and testing measures that increase operation and maintenance (O&M) burden.

Historically, poor implementation of power uprate projects has exhibited the potential to adversely impact plant reliability. Poor implementation can increase outage durations and the incidence of unplanned lost generation. If increased plant capacity reduces capacity factors, the justification for the uprate is largely nullified. Proper execution must incorporate lessons learned and operating experience (OE) to avoid human performance errors and common pitfalls associated with uprate implementation and subsequent plant operation.

Within the past 10 years, the industry has published several reports documenting the lessons learned for uprate implementation. These include NEI 08-10, "Roadmap for Power Uprate Program Development and Implementation", and INPO 09-005, "Power Uprate Implementation Strategies – Leadership Perspective" [10, 12]. Recently, EPRI has developed an uprate OE database with over 500 entries for industry use. With these tools and lessons learned, the industry has direction for improved post-uprate operational performance.

2.1.3. Regulatory

Prior to implementation of a thermal power uprate in which the licensed reactor power level will change, a License Amendment Request (LAR) must be sent to the NRC for approval of the change. It has been nearly a decade since the last SPU or EPU LAR was approved by the NRC. In the past, the review and approval timelines for some LARs took multiple years to get through the process. In addition, like any other part of the workforce, NRC staffing levels and internal knowledge to conduct these reviews have suffered from this gap in uprate projects. Couple this with the large expected wave of power uprate applications, 18-to-24 month fuel cycle LARs, Subsequent License Renewal Applications (SLRAs), and new construction and/or operating license applications, the risk of a significant NRC review backlog becomes readily apparent.

Despite these challenges to NRC review timelines, utility forecasting of uprate project LAR application submittal timelines [6] will help the NRC prepare review methodologies and staffing levels for this anticipated wave in applications. The use of AI and other recent innovative methods may also support expedited review timelines. The NRC has indicated targeted LAR review timelines of 12 months, 9 months, and 6 months for EPU, SPU, and MURs, respectively, highlighting the value of transparency and communication between utilities and the regulator for improved project planning [9].

Beyond the direct purview of the nuclear plant, grid interconnection also presents a regulatory constraint for uprate projects. Governed by the Federal Energy Regulatory Commission (FERC) or the applicable Regional Transmission Organization (RTO), new generation projects must enter interconnection queues to perform grid impact studies. Wait times in these queues continue to increase, with median durations from initial interconnection request to commercial operation currently around five years (though there is significant variability by region) [19]. Positively, multiple RTOs have shown intent to fast-track interconnection reviews for specific projects such as nuclear plant restarts and power uprates to support firm capacity on the grid [20, 21]. Early discussion with the grid regulator and entry into these queues should nevertheless be performed to ensure interconnection reviews do not impede the implementation timeline for the uprate project.

2.1.4. Supply Chain

The domestic supply chain for critical components commonly required for power uprates is not at the same level of capacity it was during the nuclear fleet buildout of the 1980s. A lack of demand and increased requirements for maintaining certifications (e.g., NQA-1) has atrophied domestic manufacturing capabilities. This has resulted in a reliance on off-shore manufacturing and procurement. These sources have faced recent additional cost pressures through increased tariffs and the larger geo-political environment. Nuclear power plants must compete with a combination of international demand, non-nuclear power plants, and other industries for the same equipment. This has resulted in significant backlogs (upwards of five years) for equipment. The longer delivery times then drive the plant's timeline to perform the uprate.

The procurement process serves as a parallel path to the engineering, design, and regulatory review process for uprate projects. Early entry into equipment queues for critical components is essential to minimize project schedule impacts for long lead items. Nevertheless, in many cases supply chain bottlenecks remain the critical path to progressing uprate projects.

Section 3 further explores supply chain challenges associated with common power uprate equipment and materials to identify current actions that utilities, suppliers, and the U.S. government can pursue to address some of these key limitations.

2.1.5. Financial

The prospect of proceeding with a power uprate project is contingent on the business case. There are several factors influencing the business case, including but not limited to the current depreciation value of nuclear plant assets, expected operating life of the unit, and end user needs. The increased life-cycle revenue for an uprate project must outweigh the overall cost. Therefore, the remaining license duration and market conditions play a pivotal role in determining what power uprate is most suitable to a specific power plant.

Major projects present a significant investment risk if not planned and executed properly. This extends beyond simple project execution, to the long-term strategic plans for nuclear plant operation. Equipment aging plays a major factor in the equation for a power uprate. Large assets such as the HP turbine, LP turbines, and generator are generally required to be replaced or retrofit to support the increased power production. Coupled with a thermal power uprate, these replacements also improve plant performance and further increase the plant's electrical power output. Therefore, the timing of these replacements with end of warranty, lowering depreciation values, and expected increased maintenance can further help justify the cost of a large power uprate. Regulatory changes to allow plants to operate beyond 60 years (SLR and potential 100-year operating licenses) can help with making the financials favorable for an uprate based on the ability of the plant to receive revenue on the project.

Demand for power has increased in recent years and is expected to continue to grow exponentially with the advent of widespread AI adoption. Hyperscalers have provided a new customer for utilities to make power uprates more viable and necessary. Beyond end user drivers, the electricity market in which the nuclear plant resides also plays a factor. A regulated market is driven by the grid operator based on the demand, also weighing the ability to produce power from a variety of sources beyond just nuclear. In a deregulated market, the unit has a bit more flexibility in producing additional power without the oversight of the Public Utilities Commission (PUC) or grid operator. However, in both cases the grid operator needs to approve the additional

power to be supplied. In certain cases, this interconnection process can take multiple years and can dominate overall project costs to prevent uprate projects from moving forward. Strategic planning between the DOE, utilities, and grid operators is essential to develop a coordinated plan for power uprates that reduces the burden of interconnection approval timelines and transmission upgrade costs.

Behind-the-meter connection presents an alternate opportunity for units to supply their power directly to end users such as hyperscale data centers. Currently this approach is facing legal challenges and undergoing regulatory review. However, if allowed, this method would provide a more effective (and potentially lucrative) pathway for a unit to supply power direct to the customer.

2.2. EVALUATION CRITERIA

In developing a structured approach to maximizing power uprate potential, evaluation criteria are largely tied to the challenges discussed earlier. Technical, operational, regulatory, and financial factors must all be considered to judge the viability of a project. The means by which to address these challenges is a product of the specific limitation; technical challenges may be better resolved through research and development activities, whereas government incentives can help justify the financials for larger uprate projects.

Within the technical domain, factors may be grouped into design and margin considerations. Reactor type and plant design have the most apparent influence on broadly defining uprate opportunities. Beyond NSSS type, core design, outage cycle frequency (18 months versus 24 months), and previous plant power uprates influence equipment margins and safety analyses. Containment design also plays a relevant role, with smaller containment volumes (e.g., PWR ice condenser containment) and lower containment design pressures often restricting uprate levels via accident analyses. While enhanced analytical methods can help to alleviate these constraints, in the near term designs must work within current regulatory confines.

Operational considerations include workforce and implementation. Workforce inexperience is a challenge faced across the nuclear industry, as well as on the regulatory and supply chain fronts. Effective project management, training, and knowledge transfer is pivotal to proper project execution.

Power uprate implementation becomes increasingly complex the more modifications there are to address. Large uprates can have upwards of ten (10) major modifications, which is bound to extend implementation outages. To reduce the burden on work planning and craft personnel, while keeping outage durations reasonable, power uprate modifications are often performed in multiple outages.

The impact of reduced equipment margins must be sufficiently understood to minimize potential effects on equipment health and reliability. Where single point vulnerabilities to generation exist, redundancies and other protections can be incorporated into the plant. Power uprate projects may also serve as a basis for performing replacements on degraded and aging components, to improve reliability and reduce the potential for unplanned trips and lost generation.

Uprate projects must consider regulatory review into the planning process. With the expected wave of uprate applications, the NRC is targeting accelerated LAR reviews to support project schedules. Increased staffing, improved review efficiency, and a standardized review process will help the NRC realize this target.

The technical, operational, and regulatory factors ultimately feed into the business case for an uprate project. Where equipment margins are exhausted, costly equipment replacement or redesign may be required. Longer project lifecycles due to slow design and regulatory reviews decrease the duration in which the nuclear plant will be operating at greater power levels, again impacting return on investment.

Cost-benefit analysis considers all of these factors, in addition to market conditions. Federal incentives can help to adjust conclusions in a variety of ways, including increasing revenue through tax credits, decreasing financing costs through low-interest loans, reducing capital cost through supply chain relief, or subsidizing extended outages for accelerated implementation. Any business case will consider the grid and market conditions to ensure the additional power can generate the revenue required.

Figure 2-1 details some of the major evaluation criteria tied to uprate project challenges.

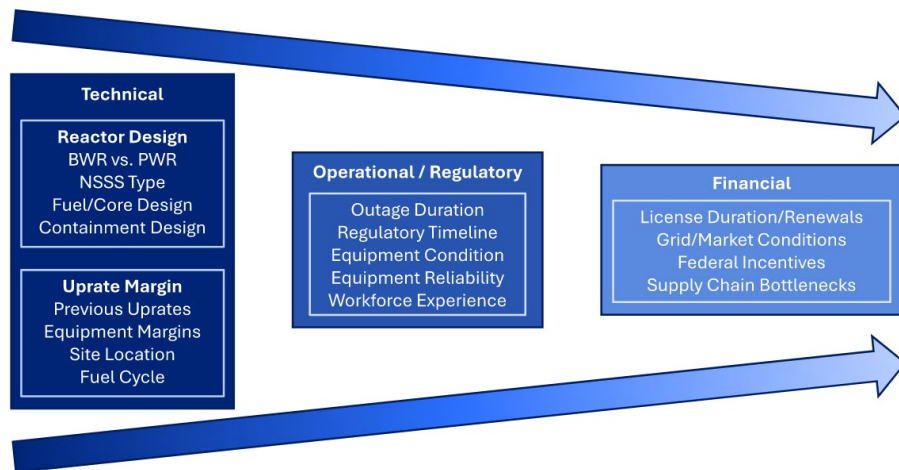


Figure 2-1. Down-selection of Technical, Operational, Regulatory, and Financial Evaluation Criteria for Power Uprates

2.3. STRUCTURED APPROACH TO THERMAL POWER UPRATES

To assist in the planning of uprate projects, as well as the development of research and federal investment to incentivize larger power uprates, the flowchart in Figure 2-2 is developed. Uprate project planning is divided into three (3) phases: plant design, margin definition/pinch point study, and financial modeling.

In the first phase, the plant design is defined to determine achievable uprate levels. This not only includes the design and licensing basis of the plant, but also the history of past uprates and the remaining license duration, which factors into the margin assessment in the second phase, and ultimately the business case.

Margin definition is rather straightforward; equipment design and analytical margins are calculated to assess the scope of modifications required for a certain uprate. Also relevant in this phase is a history of past modifications and equipment aging. Margin definition can inform the technical feasibility of a power uprate.

In the third phase, cost and risk are assessed to make the business case decision. If the evaluated uprate is either too expensive or too risky, a different uprate project should be considered.

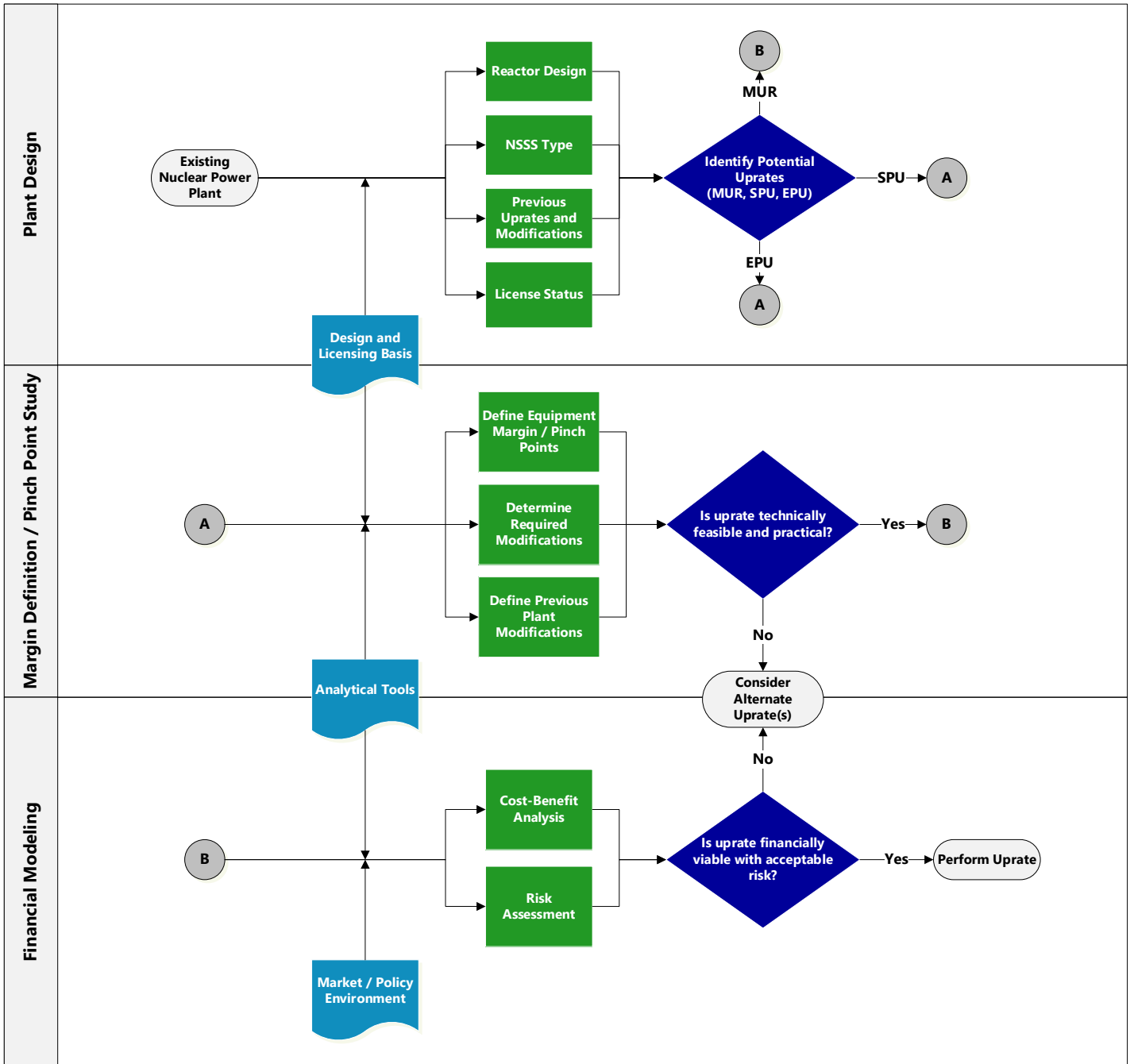


Figure 2-2. Power Uprate Planning Flowchart

3. SUPPLY CHAIN CONSTRAINTS FOR UPDATES

3.1. POWER UPDATE MODIFICATIONS

Previous efforts have attempted to summarize common equipment changes and impacts associated with power updates [14, 16, 18].

Table 3-1 below provides a near-exhaustive list of common modifications, along with likelihood of impact, that can be expected for EPU updates based on typical equipment margins. This list offers generic guidance to help focus pinch point feasibility efforts. Additional impacts may exist on a plant-specific basis.

Table 3-1. List of Common Modifications for EPU Updates

System	Subsystem / Component	Reactor Type	Common Modifications	Likelihood for EPU
Nuclear Steam Supply System (NSSS)	Steam Generator	PWR Only	Steam Generator Replacement / Modification	Low
	Steam Dryer	BWR Only	Steam Dryer Replacement / Modification	High
	Reactor Core Isolation Cooling System (RCIC)	BWR Only	RCIC Pump Trip Setpoint Changes	Low
			RCIC Snubber Replacements	Low
	Standby Liquid Control System (SLC)	BWR Only	SLC Upgrades	Low
	Reactor Recirculation Pump	BWR Only	Reactor Recirculation Pump Replacement / Modifications	Moderate
Chemical Injection	BWR Only	Zinc Injection Passivation Upgrades	Moderate	
Main Steam and Turbine Cycle	High-Pressure Turbine (HPT)	BWR/PWR	HPT Replacement	Moderate
			HPT Blade/Rotor/Diaphragm/Bucket Modification	High
			HPT Setpoint Changes	Moderate
	Low-Pressure Turbines (LPT)	BWR/PWR	LPT Replacement	Low
			LPT Blade/Rotor/Diaphragm/Bucket Modification	Moderate
			LPT Setpoint Changes	Low
	Digital Electro-Hydraulic Control System (EHC)	BWR/PWR	EHC Software/Digital Upgrades	Moderate
			EHC Setpoint Changes	Moderate
	Moisture Separator Reheaters (MSR)	BWR/PWR	MSR Replacement / Modification	High
			Moisture Separator Drain Tank Cooling Upgrade	Low
			Moisture Separator Drain Pump Modifications	Low
	Main Steam Isolation Valves (MSIV)	BWR/PWR	MSIV Replacement / Modification	Moderate
	Main Steam Control Valves (MSCV)	BWR/PWR	MSCV Replacement / Modification	Moderate
Cross Around Relief Valves (CARV)	BWR/PWR	CARV Replacement / Modification	High	

Table 3-1. List of Common Modifications for EPU Upgrades

System	Subsystem / Component	Reactor Type	Common Modifications	Likelihood for EPU
Condensate and Feedwater	Main Condenser	BWR/PWR	Waterbox/Tube Bundle Modifications	Low
			Stake Condenser Tubes	Moderate
			Increase Hotwell Level	Low
			Replace Atmospheric Relief Valve Diaphragms	Low
	Condensate System	BWR/PWR	Condensate Pump Replacement / Modification	Moderate
			Condensate Booster Pump Replacement / Modification	Moderate
			Condensate Pump Discharge Check Valve Modifications	Low
			Steam Packing Exhaust Bypass Modifications	Moderate
			Condensate Filter Demineralizer Upgrades	High
	Feedwater System	BWR/PWR	Feedwater Heater Replacement / Modification	Moderate
			Feedwater Regulating Valve Replacement / Modification	Moderate
			Seal Water Temperature Control Valve (TCV) Modifications	Low
	Heater Drain System	BWR/PWR	Heater Drain Pump Replacement / Modification	Moderate
			Heater Drain Tank Drain Control Valve Modification	Moderate
	Reactor Feed Pump	BWR Only	Reactor Feed Pump Replacement / Modification	Moderate
Reactor Feed Pump Discharge Check Valve Replacement / Modification			Low	
Auxiliary Feedwater (AFW) Pump	PWR Only	AFW Pump Replacement / Modification	Moderate	
Electrical Generation and Distribution	Main Generator	BWR/PWR	Main Generator Replacement	High
			Main Generator Stator/Rotor Rewind	High
			Generator Auxiliaries Modifications (AVR, exciter, hydrogen coolers, stator coolers, protective relaying)	High
			Main Generator Circuit Breaker Replacement	Low
	Iso-phase Bus Duct	BWR/PWR	Iso-phase Bus Duct Cooling Modifications	High
	Transformers	BWR/PWR	Generator Step-Up (GSU) Transformer Replacement / Uprate	High
			Current Transformer (CT) Replacement	Moderate
			Medium Voltage Transformer Replacement	Low
			Transformer Cooling Modifications	Low
	Switchyard and Grid	BWR/PWR	Medium Voltage Switchgear Modifications	Moderate
Switchyard Stability and Capacity Improvements			Moderate	

Table 3-1. List of Common Modifications for EPU Upgrades

System	Subsystem / Component	Reactor Type	Common Modifications	Likelihood for EPU
Heating and Cooling	Ultimate Heat Sink (UHS)	BWR/PWR	Cooling Tower Upgrades / Additions	Moderate
			Circulating/Service Water System Modifications	Low
	Heating, Ventilation, and Air Conditioning System (HVAC)	BWR/PWR	HVAC System Modifications	Moderate
Miscellaneous	Fuel	BWR/PWR	Fuel Redesign/Enrichment	Low
	Spent Fuel Pool (SFP)	BWR/PWR	SFP Cooling Upgrades	Low
	Nuclear Instrumentation	BWR/PWR	Average Power Range Monitoring (APRM) Instrument Recalibration / Setpoint changes	High
			Neutron Monitoring System (NMS) Upgrade	Moderate
	Simulator	BWR/PWR	Simulator Upgrades	High
	General	BWR/PWR	Piping Modifications	High
			Vibration Monitoring and Support Modifications	High
Instrument/Setpoint Changes			High	

3.1.1. Nuclear Steam Supply System (NSSS)

Within the NSSS scope for EPU upgrades, PWR and BWR impacts are largely independent. For PWRs, the steam generator presents one of the largest pinch points to the level of upgrade. Due to the cost of replacement, upgrades are typically kept to a level below which steam generator replacement is required. For EPU+ scenarios, however, steam generator replacement is expected.

For BWRs, the steam dryer modification is a major EPU project. Industry upgrade OE at Quad Cities [22] showed the need for site-specific evaluation to assess flow-induced vibration, structural integrity, and high-cycle fatigue concerns due to increased main steam flows for EPU. Full replacement of the steam dryer is expected to be required. RCIC component modifications are also common, while other NSSS systems such as Standby Liquid Control and Chemical Injection can be impacted depending on site conditions and whether Maximum Extended Load Line Limit Analysis Plus (MELLLA+) changes are included alongside EPU.

3.1.2. Main Steam and Turbine Cycle

The main steam system in both PWRs and BWRs experience similar flow-related impacts. HP turbine performance is strongly tied to reactor power, hence modification is typically required for any EPU. Conversely, LP turbine and MSR performance are less impacted by changes in reactor power, with modifications instead often driven by equipment age and degradation. Turbines and MSRs typically have a design life of 40 years. Many sites have already conducted efficiency upgrades (i.e., refurbishment, retrofit, replacement) that improve performance upwards of 3% based on evolved blade designs alone [23, 24]. For these sites, further major modification to the LP turbines and MSRs may not be cost-effective, whereas sites with original equipment can incorporate these efficiency modifications into EPU projects to realize additional power output.

Turbine modifications include full replacement or subcomponent upgrades to rotor, blades, diaphragms, and buckets. Setpoint and control changes may result in EHC upgrades. MSRs and moisture separators may

similarly receive full replacement or changes to MSR shell/internals, moisture separator drain pumps, moisture separator drain tank cooling, and control/relief valves. Alongside major equipment modifications, MSIVs, MSCVs, and CARVs may require upgrades to accommodate increased main steam and cross around flows.

3.1.3. Condensate and Feedwater

The main condenser, condensate, and feedwater systems experience varied EPU impacts due to increased loading, steam flow velocities, and setpoint changes. Major condenser modification is typically not required for EPU, although increased hotwell level and waterbox/tube bundle modifications may be applicable in some instances. Feedwater heaters can experience increased velocities and flow-induced vibrations that may demand replacement of nozzles, internals, expansion joint liners, or full feedwater heater replacement. Condensate polishing systems are often challenged by increased flows. Additional condensate filter demineralizer vessels or bypass lines are normally incorporated to handle the incremental capacity. BWR condensate polishing typically sees full condensate flow as opposed to the partial side-stream flow typical for PWR condensate polishing; therefore, BWR condensate polishing impacts are generally more significant.

Power train pumps including the condensate, condensate booster, feedwater, and heater drain pumps may require impeller, motor, or overall pump replacement to accommodate greater flow rates. Regulating, control, and check valves within these systems can similarly experience trim changeouts or complete replacement.

3.1.4. Electrical Generation and Distribution

On the electrical generation side, increased electricity generation associated with EPU uprate typically drives some form of modification to the main generator whether that be a stator and/or rotor rewind, upgrading generator auxiliaries, or performing a main generator replacement. Due to the increased current output, isophase bus duct conductors and cooling systems may require upgrade.

Higher power output can challenge the MVA rating of the GSU transformer, resulting in retrofit or replacement. Smaller auxiliary/medium voltage transformers and switchgear may also be affected by uprate projects. These impacts along with switchyard stability and grid interconnection need to be assessed.

3.1.5. Heating and Cooling

Cooling capacity of the Ultimate Heat Sink (UHS) can present a significant pinch point for an EPU, particularly for plants with once-through open cooling systems. Evaluation of post-uprate UHS temperature and flow rate is essential to ensure conditions remain within permitting allowances. For sites with cooling towers, retrofit or additional helper tower cells can support incremental cooling loads. Within various areas of the plant, equipment heat loads may increase, demanding upgrades to HVAC systems.

3.1.6. Miscellaneous Impacts

In addition to the common major equipment impacts, there are a number of general plant evaluations and modifications that are required for EPU projects. Plant-wide evaluation of flow-induced vibration, corrosion, and acoustic effects may demand piping and support modifications. Changes to design conditions for EPU requires widespread recalibration/updating of instrumentation setpoints, similar to SPU “paper” uprates. On

the primary side, changes to the fuel design, arrangement, and storage may also be necessary. Some sites are exploring moving from low enriched uranium (LEU, <5% enriched U-235) to low enriched uranium plus (LEU+, 5-10% enriched U-235) fuel to facilitate larger uprates in combination with 24-month fuel cycles.

3.2. MAJOR EQUIPMENT SUPPLIERS

Table 3-2 provides a short list of common suppliers for major power uprate equipment for domestic applications. Components with a low likelihood for EPU or minor modifications are not considered.

This is not an exhaustive list. Other smaller or international companies could meet these application needs.

Table 3-2. List of Common Domestic Equipment Suppliers for Major Uprate Equipment

System	Subsystem / Component	Applicable Vendors
Nuclear Steam Supply System (NSSS)	Steam Dryer	GE Vernova Hitachi, Westinghouse
	Reactor Recirculation Pump	Flowserve
Main Steam and Turbine Cycle	Main Turbines (HPT/LPT)	GE Vernova Hitachi, Siemens Energy
	Digital Electro-Hydraulic Control System (EHC)	GE Vernova Hitachi, Siemens Energy, Westinghouse
	Moisture Separator Reheaters (MSR)	GE Vernova Hitachi, Siemens Energy, TEI
	Main Steam Isolation Valves (MSIV)	Flowserve, Trillium, Velan
	Main Steam Control Valves (MSCV)	Emerson, Flowserve, Trillium, Velan
	Cross Around Relief Valves (CARV)	Emerson, Trillium, Dresser
Condensate and Feedwater	Power Train Pumps (condensate, condensate booster, feedwater, heater drain, reactor feed)	Celeros, Flowserve, Hayward Tyler, HydroAire, Sulzer, Trillium
	Feedwater Heaters	Holtec, TEI
	Feedwater Regulating Valves	Celeros, Emerson, Flowserve, Trillium, Velan
	Condensate Filter Demineralizers	Marmon Industrial Water, Ovivo, Thermon
Electrical Generation and Distribution	Main Generator and Auxiliaries	GE Vernova Hitachi, Siemens Energy
	Iso-phase Bus Duct	Crown, Powell, Electrical Builders Industries
	Generator Step-Up (GSU) Transformer	Hitachi Energy, Hyosung HICO, Hyundai Electric, Mitsubishi Electric, Prolec GE Waukesha, Siemens Energy, SGB-SMIT, Virginia-Georgia Transformer
Heating and Cooling	Cooling Towers	Cooling Tower Depot, Evaptech, International Cooling Tower, SPX
Miscellaneous	Cable	Marmon RSCC, Okonite, Prysmian, Southwire
	Anchors	Hilti

3.3. SUPPLIER INTERVIEWS AND SUPPLY CHAIN BOTTLENECKS

Some of the major uprate equipment suppliers listed in Table 3-2 above were interviewed to provide lead time status, supply chain/market challenges, and incentive opportunities to drive critical long-lead items. Where interviews were not conducted, recent vendor quotes and market experience were leveraged to support lead time estimation and market conditions. Any identifiable or business-sensitive information from these interviews has been omitted from this report out of consideration for supplier interests.

Areas of questioning explored in these interviews included the following:

- ❖ General Equipment Lead Times
- ❖ Raw Material and Manufacturing Products
- ❖ Locations of Manufacturing
- ❖ Manufacturing, Material Sourcing, Subcontracting, and Market Challenges
- ❖ Nuclear Industry-Specific Challenges
- ❖ Portion of Business Demand from Nuclear
- ❖ Projected Growth in Nuclear Demand
- ❖ Ability to Scale Production
- ❖ Additional Incentives to Expand and Accelerate Production

3.3.1. Equipment Lead Times

Figure 3-1 includes lead times for major uprate equipment at the time of this report. Supply chain conditions are highly dynamic and may yield additional variance in the coming years. Items in red have lead times exceeding two (2) years; these are potential critical path items that warrant specific attention to help expedite uprate project timelines. Lead times are from purchase order unless noted otherwise.

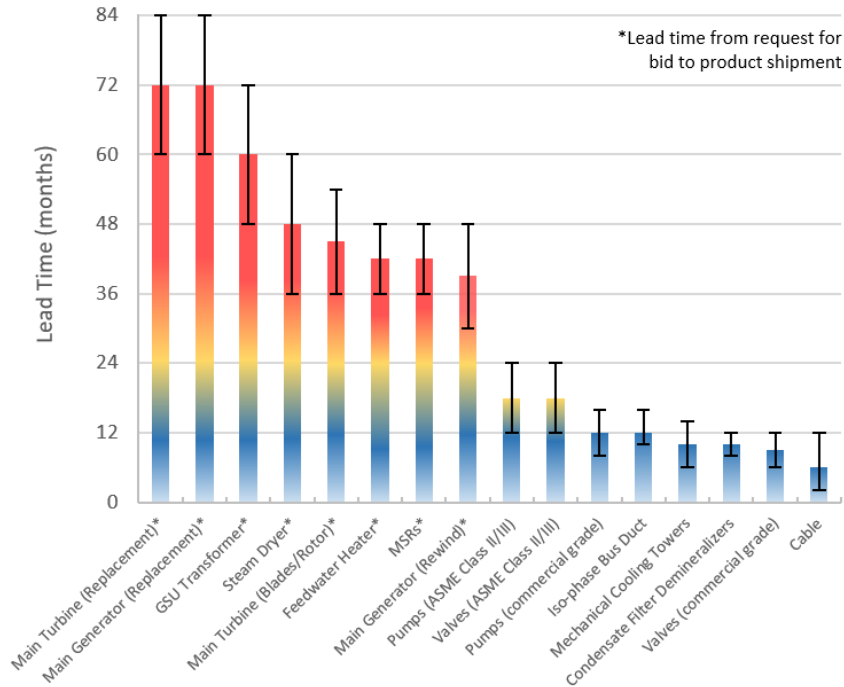


Figure 3-1. Lead Times for Major Uprate Equipment

The long lead components for uprate include:

- ❖ Steam Dryers
- ❖ Main Turbines
- ❖ Main Generator
- ❖ GSU Transformers
- ❖ MSRs
- ❖ Feedwater Heaters

3.3.2. Challenges and Incentives

Beyond lead times, interviews and S&L project experience identified the following common challenges for suppliers, along with potential incentives and solution paths:

- ❖ **(CHALLENGE) Domestic Materials/Supply:** A lack of domestic demand particularly for nuclear components, in combination with cheaper labor and greater manufacturing capabilities abroad, has led to an off-shoring of material sourcing and component manufacturing. There are limited domestic entities to support large castings for pressure vessels and valves. Tier 2 material suppliers for steel, copper, insulation, and cable, among others, have stronger international capabilities.
 - **(INCENTIVE) Reinforce Domestic Supply:** Support for domestic manufacturing would require a combination of market and demand constraints. Tariffs, subsidies, and other levers can be pulled to increase the competitiveness of domestic production in the marketplace. Similarly, material traceability and domestic content requirements can be adjusted to further incentivize projects toward the selection of domestic materials and manufacturing. While these approaches can support suppliers, they must be carefully implemented to ensure they will help accelerate project deployments as opposed to pricing out new nuclear investment.
- ❖ **(CHALLENGE) Market Uncertainty:** Free market dynamics and government intervention have significantly challenged the price and lead time certainty for many suppliers. Certain products, such as transformers, have experienced significant demand growth which has manifested itself in increasing order backlogs, Tier 2 supplier bottlenecks for critical components (e.g., grain oriented electrical steel), and greater costs. Conversely, suppliers of many nuclear grade components have been challenged by low order volume, resulting in a reduction in manufacturing capabilities, lower efficiency, and commensurate cost increases. Tariff uncertainty has amplified these cost pressures. Multiple suppliers reported poor demand forecasting within the nuclear industry specifically, which may challenge near term and long term planning of supplier manufacturing resources.
 - **(INCENTIVE) Demand Forecasting:** Improved nuclear industry forecasting of component design, engineering, manufacturing, service, and inspection needs can help suppliers better plan resources to support accelerated project timelines. This includes industry-wide new nuclear project forecasting, uprate equipment demand projection, long range plan demand projection, and improved communication with suppliers at the individual utility level.
 - **(INCENTIVE) Government-backed Demand Certainty:** In addition to improved forecasting, bulk equipment orders and government demand guarantees can ensure that sufficient order volume and demand certainty is in place.
 - **(INCENTIVE) Tariff Relief:** Tariff exemptions and relief for specific critical materials and components can alleviate supply-side cost escalation that gets passed onto end users.

- ❖ **(CHALLENGE) Nuclear Qualifications:** The American Society of Mechanical Engineers (ASME) Nuclear Component Certification (N-stamp) and Nuclear Quality Assurance Certification (NQA-1) are programs adopted by the industry to ensure that organizations delivering nuclear grade components or providing nuclear safety services conform to required quality assurance standards. Since 2015, there has been a sharp downturn in nuclear certificate holders [25]; a December 2025 review of the ASME N-stamp database (<https://caconnect.asme.org/directory/>) indicates less than 50 US-based facilities possessing nuclear certification. The reduction in new nuclear projects over the past few decades has slowed demand, reduced order volume, and challenges the justification for maintaining expensive nuclear quality programs. Suppliers with these qualifications indicated a lack of regulatory guidance and clarity in the requirements for providing nuclear grade solutions.
 - **(INCENTIVE) Regulatory Clarity and Streamlining:** Nuclear quality program requirements should be reviewed and revised to ensure clarity and minimize over-conservatism. NRC adoption of risk-informed methods can support this effort.
 - **(INCENTIVE) Expand Commercial Grade Components:** Additional guidance should be provided to expand the application of commercial grade components in nuclear facilities.

- ❖ **(CHALLENGE) Lack of Standardization:** With different reactor types, sizes, locations, and ages, there is significant variance in the choice of suppliers and equipment models across the industry. Nevertheless, there remains opportunity to standardize at both a technological and design-specific level to minimize the customization required for uprate and new build nuclear projects.
 - **(INCENTIVE) Design Standardization:** Standard design guidance should be developed to adopt technologies and designs for lifecycle cost minimization. Guidance should be provided to expand and further standardize the application of commercial grade components in nuclear facilities. Where nuclear suppliers are limited, standardized approaches to commercial grade dedication should be developed.

- ❖ **(CHALLENGE) Competing Demand:** Beyond the nuclear-specific components are a wide variety of equipment and materials common to electric power plants industrial facilities. This includes major BOP components such as turbine-generators, transformers, and switchgear, as well as commodities including steel, concrete, piping, cable, conduit, anchors, and fasteners. In specific instances, increasing demand from competing industries both domestically and abroad is driving longer lead times and equipment backlogs.
 - **(INCENTIVE) Prioritizing Nuclear Power:** Some suppliers have flexibility in equipment queues. Government consideration of nuclear power as a critical national and energy security technology can support the prioritization of nuclear components for power uprates. Financial assistance to accelerate nuclear purchase orders can alleviate order backlog time.

While these items have been specifically identified for power uprates, there are many similar themes that carry over to plant restarts and new reactors. Strong demand forecasting and support for domestic suppliers will be essential to the next phase of reactor buildout. Regulatory guidance needs to be clear and of sufficient rigor to minimize supplier burden and overdesign. Similarly, new projects should standardize the design and technology selection for balance of plant systems and components to the extent possible to minimize costly customization and leverage economies of scale benefits. Additional methods of incentivization are discussed in S&L report SL-021967 [17].

Specific challenges for some of the critical long lead items captured during the supplier interviews are discussed below.

- ❖ **Turbine Generator:** Dependent on a small number of common OEMs, the turbine-generator set experiences shared challenges. Limited availability of large castings and forgings, high global demand across both steam and gas turbine markets, qualified labor constraints, and reliance on a handful of Tier 2 suppliers has exhausted the supply chain. Lead times are increasing for these OEMs, with limited potential to scale manufacturing capabilities in the very short term.
- ❖ **GSU Transformers:** Transformer constraints are strongly influenced by material and supplier bottlenecks. Grain-oriented electrical steel, continuously transposed cable, high-density pressed-board insulation, and large bushings present significant sourcing challenges that have inhibited accelerated procurement. Domestic capacity is limited and faces competition from other large generation projects globally. Similar to the turbine-generator, recent investment in manufacturing is not expected to meaningfully expedite the supply chain in the short term.
- ❖ **Feedwater Heaters and MSRs:** With related designs and OEMs, feedwater heaters and MSRs face similar supply chain challenges. Tubing steels and forgings are difficult to source domestically at competitive cost, while Tier 2 suppliers are constrained by workforce and production capabilities. A lack of standard client specifications and weak long-term forecasting reduce project efficiencies. Lead times for these products are increasing, but remain bounded by the turbine-generator set and large transformers.

Table 3-3 provides a summary of challenges and opportunities for growth for critical uprate components, based on supplier interviews and S&L experience.

Table 3-3. Summary of Challenges and Incentives for Major Uprate Equipment Suppliers

System	Subsystem / Component	Long Lead	Supply Chain Challenges	Growth Incentives
Nuclear Steam Supply System (NSSS)	Steam Dryer*	Yes	Domestic Materials/Supply, Market Uncertainty, Nuclear Qualifications	Demand Forecasting, Reinforce Domestic Supply, Regulatory Clarity
	Reactor Recirculation Pump*	No	Domestic Materials/Supply, Market Uncertainty, Nuclear Qualifications	Demand Forecasting, Reinforce Domestic Supply, Regulatory Clarity, Expand Commercial Grade Components
Main Steam and Turbine Cycle	Main Turbines (HPT/LPT)	Yes	Domestic Materials/Supply, Market Uncertainty, Competing Demand	Demand Forecasting, Reinforce Domestic Supply, Prioritizing Nuclear Power
	Moisture Separator Reheaters (MSR)	Yes	Domestic Materials/Supply, Lack of Standardization, Competing Demand	Demand Forecasting, Reinforce Domestic Supply, Design Standardization, Prioritizing Nuclear Power
	Main Steam Isolation Valves (MSIV)	No	Domestic Materials/Supply, Market Uncertainty, Nuclear Qualifications	Demand Forecasting, Reinforce Domestic Supply, Regulatory Clarity, Expand Commercial Grade Components
	Main Steam Control Valves (MSCV)			
Cross Around Relief Valves (CARV)*				
Condensate and Feedwater	Power Train Pumps (Condensate, Condensate Booster, Feedwater, Heater Drain, Reactor Feed)	No	Domestic Materials/Supply, Market Uncertainty, Nuclear Qualifications	Demand Forecasting, Reinforce Domestic Supply, Regulatory Clarity, Expand Commercial Grade Components
	Feedwater Regulating Valves			
	Feedwater Heaters	Yes	Domestic Materials/Supply, Lack of Standardization, Competing Demand	Demand Forecasting, Reinforce Domestic Supply, Design Standardization, Prioritizing Nuclear Power
	Condensate Filter Demineralizers	No	Domestic Materials/Supply, Nuclear Qualifications, Lack of Standardization	Reinforce Domestic Supply, Expand Commercial Grade Components, Design Standardization
Electrical Generation and Distribution	Main Generator and Auxiliaries	Yes	Domestic Materials/Supply, Market Uncertainty, Competing Demand	Demand Forecasting, Reinforce Domestic Supply, Prioritizing Nuclear Power
	Iso-phase Bus Duct	No	Market Uncertainty, Competing Demand, Lack of Standardization	Demand Forecasting, Prioritizing Nuclear Power, Design Standardization
	Generator Step-Up (GSU) Transformer	Yes	Domestic Materials/Supply, Competing Demand, Transportation Infrastructure	Reinforce Domestic Supply, Prioritizing Nuclear Power, Demand Forecasting
Heating and Cooling	Cooling Towers	No	Domestic Materials/Supply, Lack of Standardization	Reinforce Domestic Supply, Design Standardization
Miscellaneous	Cable	No	Market Uncertainty, Competing Demand	Demand Forecasting
	Anchors			

* No interview/survey conducted, determinations informed from S&L market knowledge and project experience.

4. FUTURE WORK

Future work should focus on establishing the resources and knowledge base to accelerate planned uprates, improve technical and economic conditions for larger uprates, and support the transition from power uprates to new build nuclear power plants.

Near term work should explore the current opportunities for uprates within the framework of MURs, SPUs, and EPUs. Various evaluation criteria including technical, regulatory, project execution, market, and political/incentive considerations will help focus efforts on high value-proposition projects. This will focus resources in a more efficient and timely manner to meet pre-2030 capacity expansion targets. Diverse means for expediting these projects should be explored, including standard specifications for critical equipment and financial incentives to meet aggressive project implementation targets.

There has been limited recent research investigating EPU+ from both a technical and financial standpoint. As a means to move from power uprates to new builds while maintaining the nuclear supply chain and industry project knowledge, further exploration of EPU+ should be performed to better understand pinch points for both the NSSS and BOP systems. Detailed thermal hydraulic modeling can help assess project cost and risk to support industry-wide implementation of larger uprates.

5. CONCLUSIONS

Thermal power uprates have historically provided substantial capacity growth to the existing U.S. nuclear fleet. To date there have been 172 NRC-approved power uprates which have facilitated more than 8 GWe in capacity additions. Fleet experience shows that boiling water reactors have generally increased further, often operating near 120% of original licensed thermal power (OLTP) due to generic extended power uprate (EPU) guidance, while pressurized water reactors typically operate around 105% of OLTP and have realized fewer large uprates. The NRC expects approximately 2 GWe in power uprate applications through 2030. Fleet margin assessment indicates an additional 2 GWe achievable, while performance optimization modifications could further add another 1 GWe in efficiency gains. With larger EPU+ uprates, loosening regulatory constraints, and improved market conditions, there is potential for even greater capacity additions.

Realizing this capacity expansion will rely on successful project planning and execution. This report outlines a three-phase framework for power uprate level optimization based on consideration of the plant design and licensing basis, uprate history, margin assessment, and market conditions. Large stretch and extended power uprates must navigate these intertwined technical, operational, regulatory, and financial challenges to optimize uprate sizing, sequencing, and implementation such that uprates enhance capacity and improve profitability while maintaining operational excellence.

Supply chain constraints pose one of the major challenges to timely project implementation. Supplier interviews and project experience indicate long lead times for major uprate equipment including steam dryers, main turbines, main generators, generator step-up (GSU) transformers, moisture separator reheaters (MSRs), and feedwater heaters, making early entry into procurement queues essential to expedite the supply chain critical path. The domestic manufacturing base for key nuclear components has atrophied, prompting dependence on off-shore suppliers that face separate hurdles such as large order volume and tariff pressures. Market uncertainty has challenged the accuracy of project financial and schedule forecasts, while a high degree of design customization prevents significant learning efficiencies from taking effect. Mitigation of these constraints should consider coordinated demand forecasting, government-backed demand certainty, domestic supply reinforcement, targeted tariff relief, streamlined nuclear qualification requirements, expanded use of commercial-grade components, and greater design standardization across plants.

With proactive project planning, strategic policy, and supply chain support, thermal power uprates offer significant capacity expansion potential in the near-term. Establishing a robust supply chain, workforce, and knowledge base will motivate greater long-term fleet expansion. Additional research into EPU+ uprates and increased incentives for uprate projects will help accelerate project deployment and expand the U.S. nuclear capacity to achieve Executive Order targets.

6. REFERENCES

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APPENDIX A. COMMON ANALYTICAL TOOLS FOR POWER UPDATES

Detailed design and evaluation leverages a variety of computational tools. Beyond the proprietary tools used by reactor vendors and design firms, there are common software programs used throughout the industry to model plant SSCs, determine equipment impacts, and understand adjusted plant operating conditions. The below table provides a short list of commercial software used by S&L to support power uprate project design.

Function	Software Name	Developer
Computational Fluid Dynamics	STAR-CCM+	Siemens
Cooling Tower Analysis	UHSSIM	University of Illinois
Fuel Channel / Dry Cask	COBRA	Pacific Northwest National Laboratory (PNNL)
Heat Balance	PEPSE	Curtiss-Wright
Probabilistic Risk Assessment	CAFTA	Electric Power Research Institute (EPRI)
Probabilistic Risk Assessment	PRAQUANT	Electric Power Research Institute (EPRI)
Probabilistic Risk Assessment	ACUBE	Electric Power Research Institute (EPRI)
Probabilistic Risk Assessment	FTREX	Electric Power Research Institute (EPRI)
Probabilistic Risk Assessment	FRANX	Electric Power Research Institute (EPRI)
Probabilistic Risk Assessment	MAAP	Electric Power Research Institute (EPRI)
Radiological Transport/Dose Analysis	RADTRAD-NAI	Numerical Advisory Solutions
Steady State Hydraulics (Compressible)	ARROW	Applied Flow Technology (AFT)
Steady State Hydraulics (Incompressible)	FATHOM	Applied Flow Technology (AFT)
Steady State Hydraulics (Incompressible)	PROTO-FLO	Numerical Advisory Solutions
Steady State Hydraulics (Incompressible)	PIPE-FLO	Revalize Software
Steady State Thermal	PROTO-HX	Numerical Advisory Solutions
Toxic Gas/Control Room Habitability	HABIT	Nuclear Regulatory Commission (NRC)
Toxic Gas/Control Room Habitability	ALOHA	Environmental Protection agency (EPA)
Transient Hydraulics (Incompressible)	XTS	Applied Flow Technology (AFT)
Transient Hydraulics (Two-Phase)	RELAP5	Idaho National Laboratory (INL)
Transient Temperature (Compartment)	GOTHIC	Numerical Advisory Solutions
Waterhammer	IMPULSE	Applied Flow Technology (AFT)

*Note: The above list is not intended to be fully comprehensive.