



Facilitating Power Uprates at Nuclear Power Plants

Feasibility Study Guideline

2023 TECHNICAL REPORT

Facilitating Power Upgrades at Nuclear Power Plants

Feasibility Study Guideline

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EPRI Project Manager
C. Wiegand

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The following organization, under contract to EPRI, prepared this report:

MPR Associates, Inc.
320 King St., Suite 400
Alexandria, VA 22314

Principal Investigators

L. Dobrowolski
E. Federline
K. Hendershot
E. Wilmes

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ABSTRACT

Upgrading a nuclear power plant is a cost-effective and reliable way to add baseload, carbon-free energy to the electrical grid and meet aggressive climate goals. The recent economic incentives coupled with enhanced technologies have created the opportunity to upgrade plants to power levels beyond those previously achieved, challenging what the nuclear industry typically considers impassable barriers for power upgrades. Utilities should now seek to optimize their power level instead of limiting the level based on old paradigms. This optimization can be achieved only if plants thoroughly evaluate the current plant conditions, identify and differentiate pinch points from true impassable barriers, and consider all possible technical solutions before performing the cost-benefit analysis. This process is the first part of the power upgrade process—that is, the feasibility study phase.

Existing power upgrade feasibility study guidance was developed decades ago, and, although lessons learned and operating experience have informed the guidance, there are important current considerations—such as the social and economic drivers of climate change, the synergy of existing life-cycle management, and plant operational strategy (for example, subsequent license renewal)—that are not included in current guidance.

This report creates an enhanced and updated methodology for performing the feasibility study of nuclear power plant power upgrades. Readers of this report will find a process and methodology that can be readily tailored to utility power upgrade activities. Several examples are provided to aid in the implementation of the process.

The guidance and process in this report were developed by building upon historical guidance and experience and inputs from utilities, original equipment manufacturers, nuclear steam supply system vendors, specialty engineering companies, and other nuclear industry stakeholders.

Executing the process found within this report will help nuclear utilities determine the maximum technically achievable power upgrade and provide utility leadership options for choosing the optimum upgrade considering the plant overall strategy, energy market, business case, and risks.

Keywords

Extended power upgrade (EPU)
Feasibility study
Margin assessment
Measurement uncertainty recapture (MUR)
Power upgrade
Stretch power upgrade (SPU)

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PRIMARY AUDIENCE: Utility corporate and site engineers responsible for power uprate, specialty engineering company engineers, nuclear steam supply system supplier engineers, original equipment manufacturer (OEM) engineers, architect/engineer company engineers.

SECONDARY AUDIENCE: Utility executive and director level personnel overseeing power uprates.

KEY RESEARCH QUESTION

Does the existing power uprate feasibility process optimize the uprate potential of a plant and reduce plant overall risk during the power uprate implementation phase? Are the current nuclear power value propositions considered in the existing guidance? Can new methods be applied to an updated guidance that would facilitate power uprates?

RESEARCH OVERVIEW

This report creates an enhanced and updated methodology for performing the feasibility study of nuclear power plant power uprates. The feasibility study is the first step in the power uprate process and identifies a range of power uprate levels that are worth further investigation based on expected modifications. The feasibility study coupled with a business case helps utilities select the optimal power uprate level for the plant—that is, the power level with the most favorable cost-benefit ratio and an acceptable risk level over the course of the plant’s lifetime. Recent operating experience has shown that this first step, if not properly conducted, can lead to significant overrun and unforeseeable technical issues post-implementation.

This optimized guidance provides a roadmap for utilities to systematically conduct or review the key activities for the feasibility study considering plant overall strategy (for example, planned capital expenditures, subsequent license renewal [SLR]), current market conditions, risks, and financial aspects. The guidance and process in this report were developed by building upon historical guidance and inputs from utilities, OEMs, nuclear steam supply system vendors, specialty engineering companies, and other nuclear industry stakeholders.

KEY FINDINGS

- New analysis methods and technologies available to nuclear steam supply system vendors and OEMs have created opportunities to improve existing plant margin with a reasonable level of effort, which, combined with the economic and social drivers, can help extend power operation beyond what was previously considered to be the limit.
- Increasing plant power levels beyond those previously achieved will require utility willingness to be first-of-a-kind, perform more significant upgrades than those previously performed, and, if necessary, significantly extend outages to upgrade systems.
- Utilities have not taken advantage to the extent possible of existing capital projects (life-cycle management), overall plant strategy (for example, SLR) and social drivers when optimizing the power uprate level. This guidance includes detailed steps for how to incorporate these new considerations into the feasibility study.
- Examples of visuals (waterfall diagram, motivation map) are included in this report to better support the power uprate team in its decision-making process (for example, percentage of power increase to cost).

- This optimized uprate selection process will help nuclear power plant owners assess their optimal power uprate level while reducing risks in the overall power uprate process. The optimal power uprate level considers the technical (including risks) and financial feasibility of the power uprate.

WHY THIS MATTERS

Upgrading nuclear power plants provides a straightforward and sustainable reduction in carbon emissions and directly supports country and company aggressive climate goals. Because upgrading an existing power plant is faster and more cost-effective than building new plants, it can help bridge the gap on decarbonization goals until advanced technologies are ready to be deployed. An updated feasibility process will ensure that the optimum power uprate will be selected with consideration of economic and social drivers.

HOW TO APPLY RESULTS

This report provides a process that is directly transferable to a utility's procedures and processes. Readers should create a feasibility procedure or add steps to an existing procedure from the steps in this report.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Pilot opportunities will be pursued and used to inform and improve upon the existing report.

EPRI CONTACTS: Chris Wiegand, cwiegand@epri.com

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3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA

[800.313.3774](tel:800.313.3774) • [650.855.2121](tel:650.855.2121) • askepri@epri.com • www.epri.com

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POWER UPRATE FEASIBILITY STUDY**

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1

INTRODUCTION

1.1 Purpose

The purpose of this report is to facilitate uprating nuclear power plants (NPPs) by providing an updated methodology to optimize the initial power uprate decision-making step (that is, feasibility study). The goal of this process is to optimize the potential power uprate range and reduce overall risk in the power uprate process. Specifically, this report provides a roadmap for utilities to systematically conduct or review the key activities for the feasibility study considering plant overall strategy (for example, planned capital expenditures).

It is expected that the methodology herein will be used in concert with existing utility processes for optimizing the power output of existing NPPs. The appendices of this report serve as examples for how system evaluations, component evaluations, and a feasibility study could be prepared using this methodology.

1.2 Background

Realization of nuclear power's value in meeting climate goals has resulted in a need to reexamine uprating NPPs using the latest technology and methodologies.

NPPs have implemented several types of power uprates, including the following:

- Measurement uncertainty recapture (MUR)
- Stretch power uprate (SPU)
- Extended power uprate (EPU)

Power uprates have increased the output of NPPs by as much as approximately 20% over original licensed thermal power (OLTP) in the United States and approximately 30% over OLTP worldwide. The process for evaluating traditional NPP power uprates is well understood and is documented in multiple guidance documents (for example, International Atomic Energy Agency [IAEA] No. NP-T-3.9, Power Uprate in Nuclear Power Plants: Guidelines and Experience, and Nuclear Energy Institute [NEI] 08-10, Roadmap for Power Uprate Program Development and Implementation).

However, current industry guidance documents for power uprate typically cover the power uprate process at a high level. There is limited industry guidance on (1) the specific methodology that should be used to define the potential power uprate range (that is, identification of pinch

points¹ where significant investment is required to further increase power) and (2) the process to select the resultant optimal power level with consideration of existing life-cycle management (LCM) and plant operational strategy. In addition, there is little documentation on the hard stops² that limit the potential uprate of an NPP.

Additionally, published guidance documents were generated over a decade ago, and recent advances in technology and analysis methods, as well as updated industry operating experience (OE), have resulted in more efficient solutions for overcoming previously identified pinch points and may allow optimization of the potential power uprate range beyond what was previously considered. Further, recent industry OE has highlighted the importance of adequate scope definition for the power uprate process at the feasibility stage to avoid significant cost overruns and operational impacts after power uprate is implemented.

As a result, this report has been prepared to help reduce overall power uprate risk and optimize power plant uprate range by providing a structured approach to assess the feasibility of a power uprate and by identifying typical power uprate pinch points. The report highlights the key activities to ensure that utilities have a systematic and consistent approach to perform the feasibility study.

1.3 Overview of Power Uprate Project

Previous guidance documentation (for example [1, 2]) have established different phases of the power uprate process. Although these methodology documents may have different names or number of stages for the process, the overall process between documents is generally consistent. A power uprate project will typically include the steps shown in Figure 1-1. Each step is further covered in the following sections.



Figure 1-1
Diagram of power uprate project phases

¹ A *pinch point* is a limitation at which significant investment is required to further increase plant output (for example, the main generator is a pinch point component if it is required to be modified or replaced to further increase power).

² A *hard stop* is a technical barrier that cannot be overcome within reasonable means (for example, replacing the entire containment).

- **Step 1: Initial Decision-Making Process**

This step establishes the technical and financial viability of power uprate through a detailed feasibility study and economic analysis (which typically includes a business case and high-level schedule). Important considerations when performing the technical feasibility study include the following:

- Margin definition
- Review of regulatory requirements
- Current plant equipment health and long-range plan (LRP)
- Grid interface

Important considerations for the overall financial evaluation include the following:

- The existing plant LCM plan and estimated cost for planned capital expenditures
- Outage impact
- License renewal
- Energy market (for example, projected power demand and power prices for the region in which the NPP is located)
- Carbon-free production incentives

The feasibility study will define a range of power levels for uprate that are worth further investigation based on expected modifications (that is, the uprate study will identify various pinch points at which significant modifications are required to further increase power output). From this, a business case is performed to select the optimal power uprate level for the plant considering the financial (for example, cost-benefit ratio) and risk assessment of each uprate scenario, along with the company's objectives and market forecast.

- **Step 2: Project Development and Management**

After the target power level has been selected, the project mobilization phase occurs to coordinate the necessary resources for a successful project. During this phase, the organization structure (including oversight) is established for the project. Scope, deliverables, communication plan, risk strategy, procurement strategy, and quality requirements are clearly defined, and an integrated schedule is produced with key milestone targets established for License Amendment Request (LAR) submittal, LAR approval by the regulator, and implementation.

The schedule should also consider a procurement plan for major long lead time equipment to be scoped, analyzed/sized, and specified and for bid evaluations (if required), purchase order issuance, and delivery.

- **Step 3: Analysis and Design Work**

After the project setup has been established, detailed analytical studies and design work can begin for the optimal power uprate level. This detailed design work should build upon the technical feasibility study to determine all required modifications and impacts to the plant as a result of power uprate. Key areas to target for this work include the following:

- Fuel impact
- Nuclear steam supply system evaluations
- Emergency core cooling systems evaluations
- Balance-of-plant (BOP) evaluations
- Nuclear steam supply system/BOP interfaces
- Grid interfaces
- Safety/containment, radiological, and program analyses

At the end of this step, the utility has developed the safety analyses and component modifications packages that are needed to implement the power uprate.

- **Step 4: Licensing**

To implement a power uprate, a utility must submit a LAR that reevaluates the plant's current operating license for the increased power level. There are several industry documents (see Section 3.1) to guide utilities through this process; in general, regular and early communication with the regulator is key for a successful licensing process.

- **Step 5: Implementation**

After the relevant modification packages have been developed, plant personnel will begin to implement the changes necessary to accommodate the increased power level. In some cases, power uprate implementation will require plant modification over multiple outages, the sequencing of which will need to account for outage time, location of work within the plant, and operation of upgraded equipment at current licensed thermal power (CLTP) rather than uprated conditions. Other factors to consider are overall plant strategy (for example, subsequent license renewal [SLR]) and other utility fleet outages (if applicable). For multiple outage implementation, the utility should prioritize implementation of modifications that provide near-term performance or reliability improvement. Detailed guidance on the implementation process can be found in other guidance documents ([1, 2] for example); these guidance documents cover areas such as outage planning, training and simulator upgrades, procedure updates, power ascension testing and monitoring, plant data trending, startup vibration monitoring, and thermal performance testing.

1.4 Report Scope

This report focuses on Step 1: the Initial Decision-Making Process covered in Section 1.3. Specifically, it provides detailed guidance to perform the feasibility study to better inform plant personnel of the potential power uprate range (including component pinch point identification and methods to overcome them). Further, it provides guidance for selecting the optimal power uprate level from the potential power uprate range by considering the plant LCM strategy and system interactions for potential uprate modifications, as well as company's objectives, market forecast, and the more traditional financial evaluation and risk assessment.

Other phases of the power uprate process are outside the scope of this report because they are well-defined in existing guidance documentation. It is noted the technical guidance included herein may also be useful during the detailed analytical studies conducted in Step 3 in addition to the initial feasibility study.

1.5 Report Approach

This report develops a methodology for utilities to systematically conduct or review the key activities for the feasibility study using the following approach:

- Review existing industry guidance documentation for determination of potential power uprate range and selection of optimal power uprate level.
- Survey industry utilities to identify (1) historical limitations to the power uprate process and strategies that were used to overcome them and (2) technical issues that industry has faced during the power uprate process.
- Review industry databases (EPRI, Institute for Nuclear Power Operations [INPO], World Association of Nuclear Operators [WANO], and so forth) to complement industry utility surveys, with a focus on the technical challenges that utilities faced after a power uprate.
- Interview nuclear steam supply system vendor personnel involved in power uprates regarding potential hard stops that limit the power level for an uprate (A nuclear steam supply system vendor should be engaged early on to help develop the feasibility study for nuclear steam supply system design impacts.).
- Using the results of the prior steps, develop detailed guidance to generate the potential power uprate rate on a system and component basis.
- Develop guidance to best select the optimal power uprate level, including consideration of plant's existing LCM and operational strategies and system interactions when evaluating potential plant modifications.

2

POWER UPRATE HISTORY AND MOTIVATION

This section summarizes historical details related to uprating plants from their OLTP, provides an overview of the global power uprate history, and covers the recent motivation for reexamining the potential for further uprates.

2.1 Plant Margin

NPPs have historically been constructed with large design margin, which has created the opportunity to increase power beyond the OLTP. These large design margins have been used to increase plant electric generating capacity while maintaining safety margins, plant performance, and reliability (that is, production margin).

Plants use margin in the design space and in defining operational limits to ensure (1) compliance with plant and regulatory requirements and (2) consistency with design bases. Figure 2-1 illustrates the concept of operating margin, design margin, and analytical margin, as follows:

- *Operating margin* is the difference between the normal operating point of a system and its operating limit.
- *Design margin* is the difference between the analyzed design limit to ensure safe operation of a system, structure, or component (SSC) and the operating limit.
- *Analytical margin* is the difference between the analyzed design limit and the ultimate capability of an SSC.

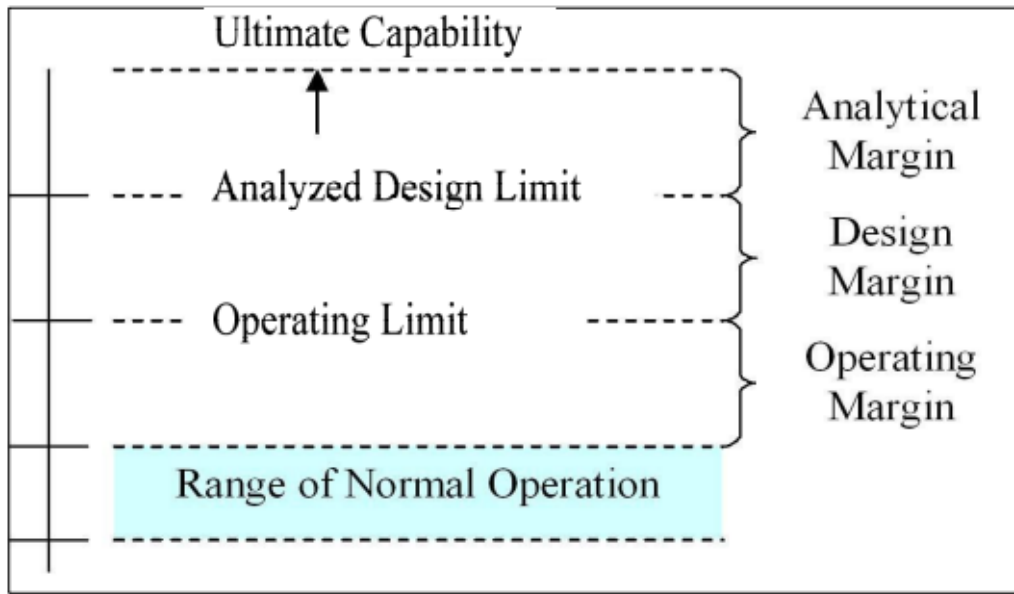


Figure 2-1
Schematic of plant margins [3]³

Analytical and design margins ensure that plant operation remains within design requirements and design bases, respectively.

Power uprate projects will tend to increase the range of normal operation. As the margin between the maximum operating condition and analyzed design limit is reduced, plant personnel will need to determine the threshold at which margin can no longer be reduced without additional actions. These actions may include component upgrades or reevaluation of safety analysis with advanced analysis methods to increase plant design limit and, therefore, recover plant margin. Note that equipment upgrade tends to also increase reliability as in many instances, the equipment upgrade will address existing reliability concerns. Plants have leveraged power uprates to eliminate single point vulnerabilities wherever possible.

2.2 History of Power Uprates

NPPs have leveraged the relatively large design margins inherent in most nuclear plant designs to uprate the plant and generate additional carbon-free power. Three types of power uprates have been used: MURs, SPUs, and EPU. These uprates are covered further in the following sections.

2.2.1 MUR Power Uprate

MUR power uprate (also referred to as *10CFR50 Appendix K uprate*) is a power increase up to 2% that is achieved by implementing enhanced techniques for calculating reactor thermal power.

Calculation of core thermal power typically relies on accurate measurement of various inputs, specifically feedwater flow. To account for uncertainty in data measurements (mainly feedwater venturi flow meters), regulations (for example, 10CFR50 Appendix K in the United States) have

³ The technical specification (TS) limit is not shown in Figure 2-1 but is between the analyzed design limit and the operating limit, where applicable.

required utilities to assume a thermal power level that is at least 1.02 times the licensed power level for safety analyses. Since original plant construction, state-of-the-art ultrasonic feedwater flow measurement devices have reduced the degree of uncertainty in the flow rate and, therefore, the power level. Alternatively, new techniques such as data validation and reconciliation (DVR)⁴ have been implemented internationally to reduce uncertainty in instrumentation and the calculated power level. As such, regulatory commissions (for example, the U.S. Nuclear Regulatory Commission [NRC]) have allowed plants to recover the measurement uncertainty and slightly increase thermal power level. This uprate typically requires a limited number of modifications (for example, upgrade of the flow measurement devices, DVR software).

2.2.2 Stretch Power Uprate

SPUs are typically up to a 7% increase in power and use existing design margin in the plant. The actual increase in power that a plant can achieve and stay within existing design margin depends on the operating margins included in the design of a particular plant. SPUs usually involve changes to instrumentation setpoints but do not typically involve major plant modifications.

2.2.3 Extended Power Uprate

EPU are greater than SPUs, with historical increases as high as approximately 122% plant OLTP in the United States⁵ and about 130% OLTP worldwide. To produce this additional electricity, steam flow must be increased substantially. The thermal power generated in the reactor core must be similarly increased, which is accomplished by increasing the average power density within the core. The core power distribution is flattened while limiting the absolute power in the individual fuel bundles to allowable values. The increased operating power can affect operating flexibility and reactivity characteristics; so, countermeasures are usually taken. This process can include modifying the loading pattern of the core, using larger batch sizes, introducing new fuel designs and fabrications, increased use of burnable poisons, and reducing jet pump leakage (in boiling water reactors [BWRs]).

Because the increase in power and steam flow is significant, large plant equipment typically needs to be modified or replaced to eliminate pinch points that would otherwise limit further increases in power. Typically, modifications to major BOP equipment include steam turbines, condensate pumps and motors, main generators, transformers, moisture separator reheaters, and isophase bus duct cooling. Nearly all EPUs require a retrofit of the high-pressure turbine steam flow path to increase flow passing capability/capacity.

2.3 Current U.S. Industry Status

Since the 1970s, the majority of U.S. NPPs have received regulatory approval to increase the thermal output of the reactor, thereby increasing the amount of electricity that can be generated. To date, the U.S. NRC has approved 171 power uprates totaling over 24,000 MWt [8].

⁴ The DVR relies on existing redundant measurements in the thermodynamic cycle and statistical regression to minimize uncertainties and obtain a reliable and accurate calculation of core thermal power [4–7].

⁵ The ~122% uprate of Peach Bottom is the result of the plant performing an MUR after the EPU. The EPU allowed Peach Bottom to operate to 120% of the OLTP, and then the MUR increased the plant power by an additional 1.7%—that is, ~122% of the OLTP.

The thermal power gained through power uprates for operational BWRs and pressurized water reactors (PWRs) at the time of this report is shown in Figures 2-2 and 2-3, respectively. In total, BWRs have gained more than 13,000 MWt through power uprates, despite having approximately half the number of reactors as PWRs [8]. This is driven by the fact that the NRC has approved a generic approach to EPU for BWRs including specific criteria, analysis codes and methods, assumptions, and scope through General Electric power uprate reports [9–11]. As a result, BWRs are able to increase power up to 120% OLTP without significant modification to nuclear steam supply systems by increasing core flow along the maximum extended load line limit analysis rod line to the maximum licensed core flow. Analogous EPU guidance has not been published for PWRs. Further, PWRs have historically been limited in uprate capacity by available margin in the steam generators. Operators of many PWRs have chosen to limit uprate capacities to avoid making major modifications or replacements to steam generators based on cost and risk.

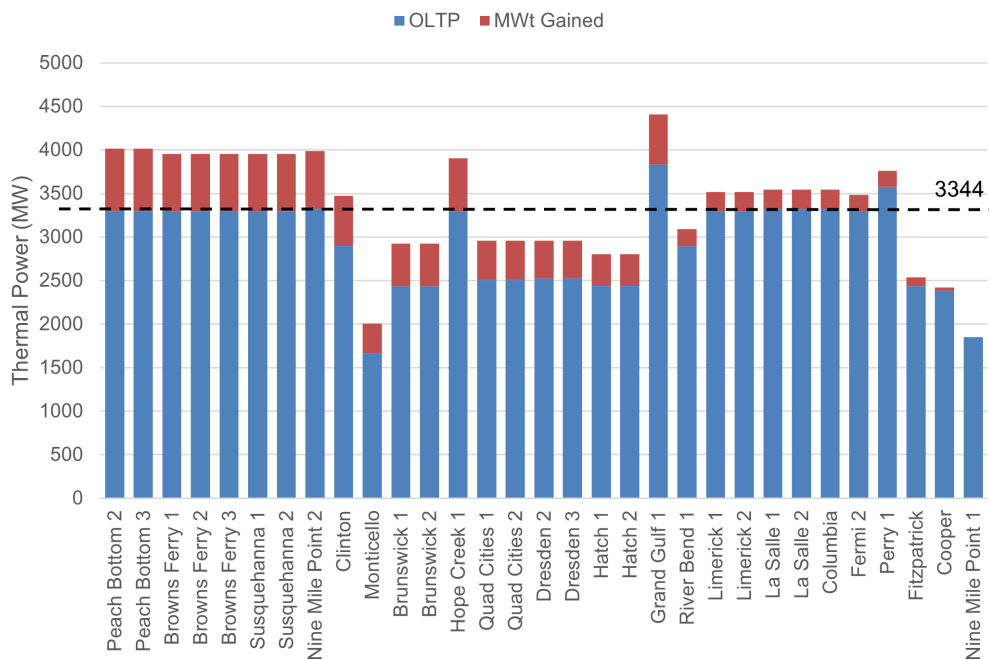


Figure 2-2
CLTP for operational BWRs in the United States (dashed line indicates average CLTP)

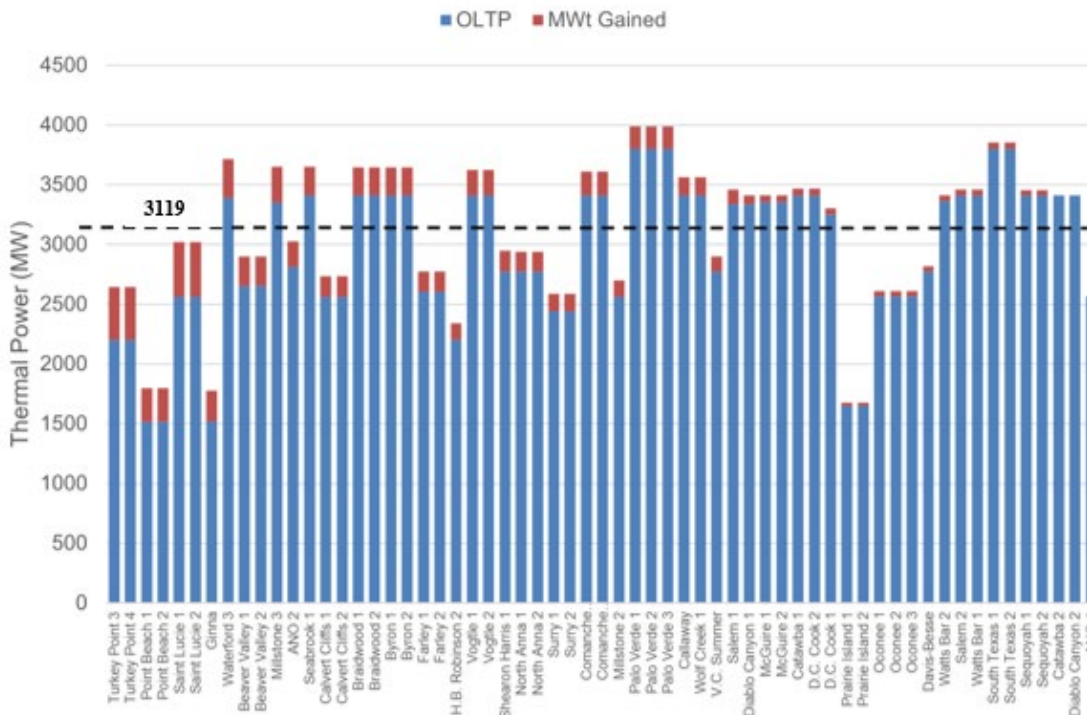


Figure 2-3
CLTP for operational PWRs in the United States (dashed line indicates average CLTP)

Another way to visualize the effect of power uprates is through the total percent uprate beyond OLTP. Figures 2-4 and 2-5 show the total percent uprate beyond OLTP for all operational BWRs and PWRs in the United States, respectively. As Figures 2-4 and 2-5 show, the average BWR uprate is to 114% OLTP and the average PWR uprate is to 106% OLTP. The difference in power level between similar reactor designs is evidence that opportunities exist for continuing to optimize the thermal output of the current U.S. operational fleet.

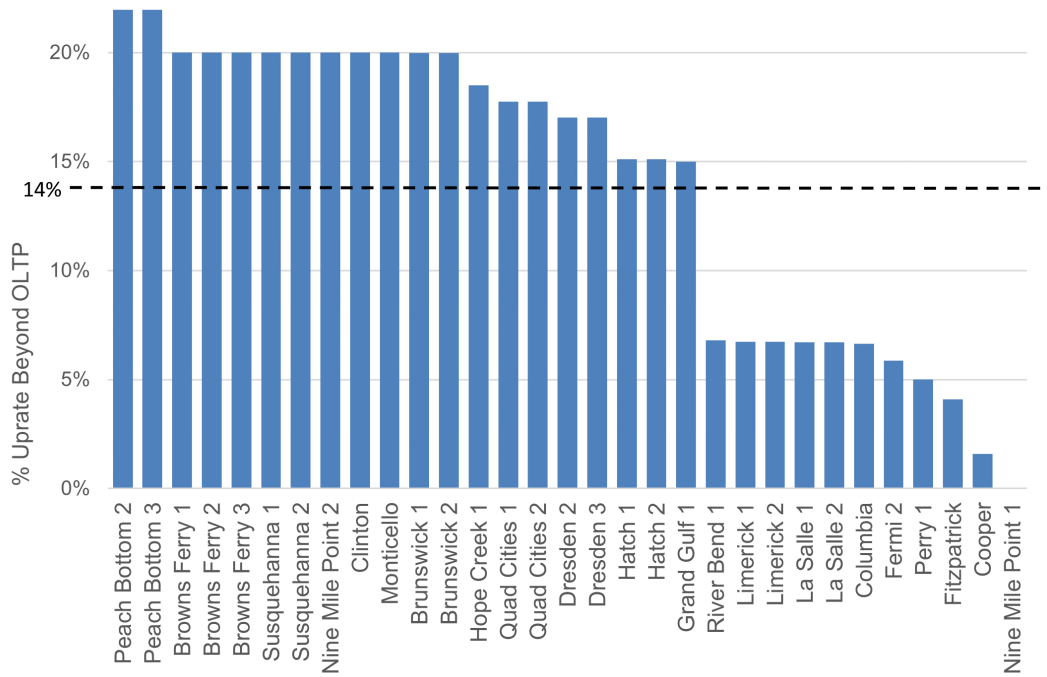


Figure 2-4
Total percent uprate for operational BWRs in the United States (dashed line indicates average)

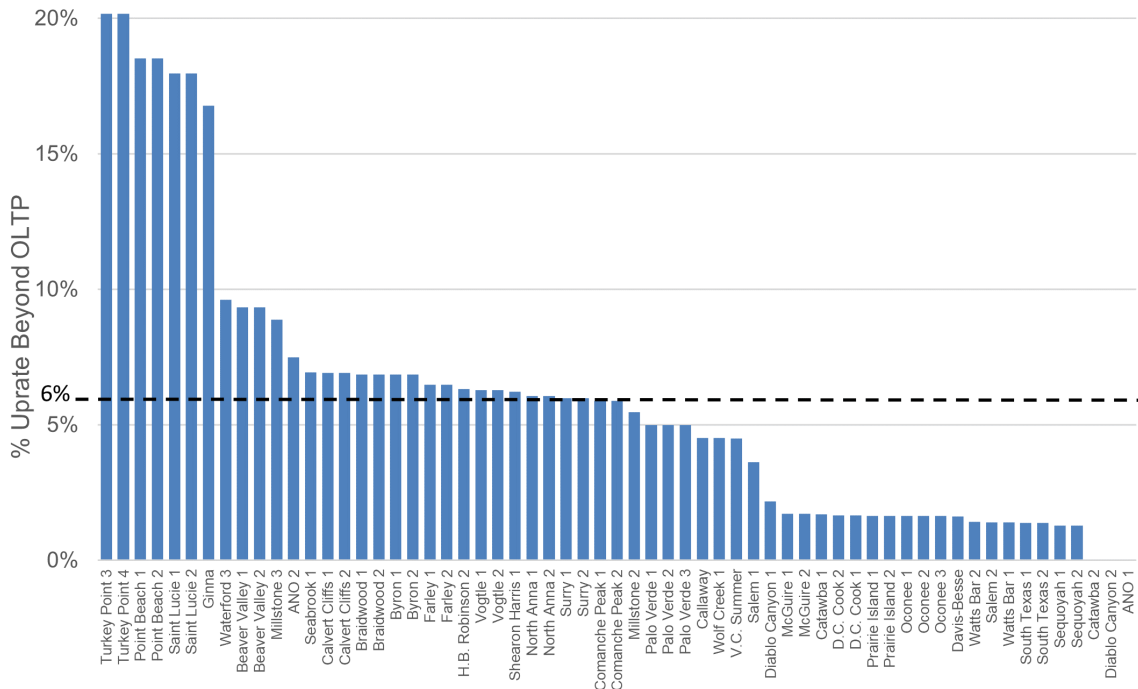


Figure 2-5
Total percent uprate for operational PWRs in the United States (dashed line indicates average)

2.4 International Power Uprates

NPPs outside the United States have also capitalized on the opportunity to increase generating capacity by uprates. More than 45 international reactors have been uprated to date. Examples of power uprates that are being used across the world include the following:

- All operating reactor units in Switzerland have been uprated, which has increased the country's nuclear capacity by 13.4%.
- Hungary, Mexico, Slovakia, Slovenia, and Spain have uprated all of their operational reactors.
- Units in Sweden (Oskarshamn 3) and Finland (Olkiluoto 1 and 2) have surpassed the historical limitation of 120% OLTP and increased thermal power by 29.1% and 25%, respectively.
- Other countries, including Argentina, Belgium, Canada, and South Korea, have also uprated reactors to a lesser extent than those mentioned previously.
- China, France, India, Japan, Russia, and South Korea account for more than 200 reactors collectively, but fewer than 10 plants have performed power uprates.

2.5 Current Drive for Power Uprate

EPU in the United States began in the late 1990s, with the majority finalized over a decade ago. From around the time these EPUs were implemented until recently, market conditions had not been favorable to the U.S. nuclear industry, with natural gas prices at historic lows and subsidies for wind and solar energy in the form of tax credits. As a result, many utilities limited the capital investment for EPUs to ensure a positive return on investment within the plant's operating life. EPUs for some plants were canceled after having been previously deferred due to the large investment required and the uncertainty in the nuclear market (for example, LaSalle Units 1 and 2, Limerick Units 1 and 2, and Forsmark Unit 3).

In addition to economics, OE has shown that large power uprates, if not properly planned/evaluated, can lead to derating and forced plant shutdowns, which has led to additional licensing scrutiny. Based on this experience, some plants have opted to uprate to similar power levels as plants of similar design regardless of their existing safety margins or the favorable return on investment from going to a higher power level. In other words, some plants have intentionally limited their present power output in an effort to avoid uncertainty in operating beyond power levels at which similar plants have operated reliably. These factors have significantly slowed the frequency of power uprates, and, for some plants, plant capacity remains available.

The landscape today is significantly different and requires a different perspective when considering the optimal power uprate than previously taken. Specifically, the intrinsic value of nuclear in meeting climate goals (for example, U.S. Inflation Reduction Act, state carbon emission requirements) provides a new driver for uprating, or at least, a new driver for the initial decision-making process. Additionally, subsequent (and potentially second subsequent) license renewal provides for an additional time horizon that may equal the original life of the plant. As a result, power uprates currently present a compelling financial, political, and environmental way to bridge the gap on decarbonization goals until advanced technologies are ready to be deployed. The recent favorable market conditions for nuclear power are causing some nuclear steam supply system vendors to resume internal discussions to uprate existing units beyond those previously achieved for a given nuclear steam supply system design. Some vendors initiated these internal

discussions in the 2010 time frame but stopped after the Fukushima accident and the arrival of less favorable economic conditions. New analysis methods and technologies available to nuclear steam supply system vendors and original equipment manufacturers (OEMs) have created opportunities to improve existing plant margin with a reasonable level of effort and extend power operation beyond what was previously considered to be the limit (for example, 120% for BWRs). As a result, many technical areas previously considered hard stops show that additional margin or modifications are now technically feasible and may be financially justified given the current market for power uprates.

Therefore, it is critical that existing nuclear plants move beyond the historical paradigm around what is or is not possible and reasonable in a power uprate. For example, the reactor recirculation system is typically considered an impassable barrier for power uprates because of the complexity of the upgrade (for example, outage length, cost). However, this system was recently replaced, out of necessity for operation, at an NPP in Switzerland during a 194-day outage. This outage duration would be an impassable barrier for a power uprate project that looks at return on investment. However, this upgrade demonstrates that the project is technically feasible and, therefore, should be considered a pinch point rather than an impassable barrier.

Increasing plant power levels beyond those previously achieved will require utility willingness to (1) be first-of-a-kind, (2) perform more significant upgrades than those previously performed, and (3), if necessary, significantly extend outages to upgrade systems. Applying this perspective to traditionally considered hard stops, as covered previously, will allow plant personnel to optimize the power uprate level rather than limit the level based on old paradigms. This can be achieved only if plants thoroughly evaluate the current plant conditions, identify and differentiate pinch points from true hard stops, and consider all possible technical solutions before performing the cost-benefit analysis.

The necessary change in posture of the nuclear industry and the lessons learned from previous uprates have resulted in the need for detailed guidance to reduce overall risk and optimize future uprate projects.

3

OVERVIEW OF OPTIMIZED POWER UPRATE INITIAL DECISION-MAKING PROCESS

This section summarizes the existing guidance for power uprate feasibility studies and provides an overview of the optimized decision-making process for evaluating the feasibility of a power uprate.

3.1 Current Industry Guidance

As covered in Section 1.3, the first step in the overall power uprate project is to conduct the initial decision-making process to determine the optimal power uprate level for the plant. This optimal power uprate level is generated through a technical feasibility study that produces a potential power uprate range with varying degrees of modifications, followed by a financial evaluation and risk assessment to down-select to the target power uprate level.

Existing industry documents provide general guidance on conducting the feasibility study. Publicly available industry guidance includes the following:

- NEI 08-10 [1]
- IAEA NP-T-3.9 [2]
- INPO 09-003 [3]
- GE NEDO-32424 [9]
- WEC NS-ES-0020 [12]
- INPO 09-005 [13]

These guidance documents highlight the power uprate process with an overview of the analytical work and considerations for the target power uprate. However, detailed guidance for generating the initial power uprate range (the identification of plant pinch points—especially for BOP components) and specific decision-making guidance for selecting the appropriate target power level are outside of their scope.

3.2 Optimized Initial Decision-Making Process Overview

The initial decision-making process of the power uprate is critical for a successful power uprate project. Inadequate scope definition can lead to significant cost overruns during the implementation process, as well as unforeseen technical issues post-implementation. To mitigate these risks, this report provides a detailed approach to optimize generating the potential power uprate range and down-selecting to the target power uprate level. Further, this approach aims to optimize the potential power uprate range. Industry OE indicates that some utilities have limited the range of potential power uprates based on historical industry power uprates or OEM input prior to performing the detailed feasibility study (for example, targeting the same power level of a plant of the same design regardless of the actual plant margin).

The approach presented in this section is intended to define the potential power uprate range considering the available margin in the plant as determined by the feasibility study, rather than starting from a power uprate selected with limited assessment of plant margin. Further, the process takes into account overall plant strategy, including LCM modifications that would be made independent of power uprate. The process is performed with the following five steps:

1. Define feasibility study scope.
2. Perform LCM screening.
3. Assess margin for power uprate.
4. Define potential power uprate range.
5. Select optimal power uprate level.

An overview of each step is provided in the following sections with detailed instructions for each step in Section 4.

3.2.1 Define Feasibility Study Scope

The first step of the initial decision-making process is to identify the key SSCs that will drive the main technical challenges and capital expenditures associated with a power uprate. At this stage of the power uprate evaluation process, it is not practical or necessary to evaluate every plant SSC for power uprate. Instead, the scope should identify key SSCs (for example, whose upgrades are expected to exceed \$1M) that will be affected by a power uprate.

To generate this initial scope of SSCs, the following factors should be considered:

- Potential that the SSC impacts nuclear safety or generation (for example, failures of the SSC have historically resulted in significant generation loss for the unit and/or the broader fleet of similar reactor style)
- SSCs that have been historically problematic for the plant are known to be single point vulnerabilities or are expected to require a significant investment to ensure reliable operation of the plant through end of plant life

It is important to establish a sufficiently broad set of systems to include in the power uprate feasibility study to ensure that the pinch points are accounted for in the potential power uprate range. As such, during this step, utilities should also review plant programs (for example, flow-accelerated corrosion (FAC), heat exchanger performance and integrity, large motor, and so

forth) because these could reveal components that have reliability issues or low margin and may be pinch points.

Table 3-1 includes examples of typical systems that are to be included in the study based on industry OE. Personnel from each plant should perform their own site-specific assessment to inform their scope selection. Table 3-2 shows a list of typical plant programs to include in the feasibility study review.

Table 3-1
Typical SSCs to Include in power uprate feasibility study

SSCs
AC distribution system
Condensate system (for example, demineralizer, pumps)
Cooling water systems (for example, circulation, service water)
Feedwater system (for example, feedwater heater [FWH], pump, regulating valve).
Fuel
Heater drain system
Isophase bus duct cooling
Generator circuit breaker
Generator step up transformer
Main condenser
Main generator (including voltage regulator and exciter) and auxiliary systems
Main steam system
Main turbine (including auxiliary systems)
Moisture separator/moisture separator reheater
Nuclear boiler instrumentation
Nuclear steam supply systems
Power range monitors
Primary containment cooling
Reactor feedwater system and instruments
Reactor recirculation and adjustable speed drives
Spent-fuel storage
Steam dryer (BWR)
Steam generator (PWR)
Switchyard
Turbine building heating ventilation and air conditioning

AC = alternating current

Table 3-2
Typical programs to review during power uprate feasibility study

Programs
BWR Vessel Internals Project program
FAC program
Heat exchanger performance and integrity program
Heat exchanger performance testing (Generic Letter 89-13)
Large motor program
Large pump program
Relief valve program
Setpoint program
Thermal performance program

3.2.2 Perform LCM Screening

It is important during the power uprate feasibility study to understand existing LCM projects that are planned for SSCs that may be impacted by a power uprate. If the power uprate margin assessment determines that a key SSC needs a modification as a result of power uprate, but the component is already scheduled to be modified or replaced for LCM purposes (for example, aging issues), the costs for power uprate may be synergized, improving the overall business case for power uprate. Additionally, these SSCs scheduled for modifications or replacements can be removed from the margin assessment if the LCM project can accommodate the upgrade.

Therefore, prior to the initial margin assessment, utilities should conduct the following LCM assessment:

1. Review the plant's current list of long-range capital projects (herein referred to as *long-range plan* [LRP]) as a basis for understanding the current planned modifications or replacements for the relevant systems identified in the prior step. The LRP should consider the expected plant operating lifetime. For example, if a utility intends to pursue SLR, the required upgrades to operate the plant through the proposed second period of extended operation should be included in this assessment.

Assess current plant condition through interviews with plant personnel (for example, system engineers) and documentation review (for example, plant corrective action data) to identify SSC performance/material issues that may require additional LCM projects beyond those included in the LRP. Note that if the LRP did not encompass capital projects through the end of the expected plant operating lifetime, it is expected that additional LCM projects will be identified and added.

2. Using the results of the preceding steps, identify the LCM projects that may be necessary to reach end of plant life, independent of power uprate.

At the end of this step, plant personnel will have a refined scope of components to include in the margin assessment—components that will be modified as part of an LCM project (that is, independent of power uprate) can be designed to the target output power level; therefore, detailed margin assessment is not required. The scope of the margin assessment is, therefore, limited to the key components that are not scheduled for significant LCM modifications or replacement. This process makes the margin assessment, which is described in Section 3.2.3, more efficient.

3.2.3 Assess Margin for Power Uprate

Prior to assessing the impact of power uprate, plant personnel should identify the current condition and margin for the components that will be impacted by power uprate. As covered in Section 2.1, plants have historically leveraged the inherent margin in NPP designs to support a power uprate. Therefore, for the systems impacted by a power uprate, the design, operating, and safety margins for key components need to be assessed.

It is recommended that key SSC parameters that will be impacted by power uprate be documented in a table along with their associated limits (that is, operational, design, and TS limits). After they are documented, the parameters can be analyzed for uprate conditions. This will provide a maximum power uprate level before limits are exceeded.

These assessments for determining the impact on an SSC parameter should be scoping in nature and used to identify the current key margin constraints within the plant. The key SSC parameters at the uprate conditions (for example, pump flow rate and discharge pressure) should be derived from either plant models or hand calculations. For example, the increase in mass flow rate for the condensate, feedwater, and main steam systems may initially be assumed to be proportional to the increase in power.

Additionally, prior to or in tandem with this step, plant personnel will need to identify the margin management strategy for SSCs. Specifically, plant personnel will need to determine what amount of remaining margin is acceptable, because changing operating parameters to operate right at operation/design/TS limits is likely not an acceptable level of risk. There may also be some instances when operating near the limits is acceptable if compensatory measures are taken to mitigate the risks (e.g., increasing monitoring frequency). These pinch points are typically referred to as “soft” pinch points.

Subject matter experts (SMEs) and experienced plant personnel should review the conclusion of the system-by-system margin review. Experienced plant personnel will need to confirm that the conclusions reached in the margin characterization are consistent with the actual plant performance.

An example of how to perform this step for the condensate system, a system that typically has multiple pinch points for a power uprate, is provided in Appendix A of this report.

At the end of this step, plant personnel will have (1) the current margin for key SSCs and (2) the maximum power uprate that each of these key SSCs can accommodate as currently designed.

3.2.4 Define Potential Power Uprate Range

Leveraging the margin assessment, plant personnel should identify the pinch points—that is, the components for which a modification or replacement requiring significant capital investment (for example, greater than \$1M) is necessary to support further increases in power. For each pinch point, modification strategies will need to be developed; these could range from partial modifications to component replacement to complete system overhauls. Modification strategies should (1) ensure that the optimal potential power uprate range is generated and (2) inform the overall cost estimate for each power uprate scenario. Example guidance is provided in Appendix A of this report for developing modifications for key SSCs of the condensate system. Key considerations when defining the potential power uprate range include the following:

- Plant systems and components interdependence must be considered. It is important to understand how a change in an SSC impacts the plant holistically when defining the uprate scenarios. For example, replacing a pump to increase flow capacity could cause the associated piping to become a pinch point. In certain cases, some of the margin from a key component may be regained by upgrading a component from another system (for example, a condensate pump could operate closer to its best efficiency point (BEP) after an upgrade of the FWHs that reduces pressure losses).
- Among the pinch points, there are components that will drive the upper bound of the potential power uprate range because of technical, cost, and/or risk constraints. These typically include the main generator, main turbine, steam dryer (BWR), main condenser, and steam generator (PWR). These component margin assessments should be performed first; other components (for example, FWHs, condensate pumps) can be designed to accommodate the expected increase in power output for the components that drive the upper bound of the potential power output range. Therefore, evaluating components that will drive the upper bound first will better inform the scope of modifications for other components identified as pinch points, which allows for a better estimate of the financial impact of those component modifications.
- After the uprate scenarios have been developed (with their corresponding power output), each component that was identified as a pinch point below the maximum potential power output⁶ should be evaluated to confirm that a replacement or upgrade is feasible. Similarly, for these components that were not evaluated in the margin assessment due to existing LCM projects (see Section 3.2.2), plant personnel should confirm that a replacement or upgrade to the maximum potential power output is feasible.

At the end of this step, plant personnel will have a potential power uprate range (that is, potential power uprate levels with pinch points and strategies to overcome them). This potential power uprate range is typically depicted with a waterfall chart that plots power uprate costs versus power level (see Section 4.4 for an example).

⁶ The *maximum potential power output* refers to the uprate scenario that results in the greatest thermal power output. For example, Pump A may be a pinch point at 106% CLTP while Heat Exchanger A drives the upper bound of the various uprate scenarios at 112% CLTP. The maximum potential power output is 112% CLTP. Therefore, Pump A should be evaluated at 112% CLTP to confirm that a replacement or upgrade is feasible at this power level.

3.2.5 Select Optimal Power Uprate Level

At this stage of the feasibility study, utilities typically develop a business case for each power level scenario to select the optimal power uprate level for their site. The business case usually includes a detailed financial evaluation (for example, net present value [NPV], payback period, rate impact) and risk assessment for each power level scenario. The business case may also compare power uprate to other sources of energy (small modular reactor, renewables, and so forth) with leveled cost metrics. The optimal power uprate level is then selected in accordance with an established approval process that considers the output of the financial and risk assessments.

In some instances, the optimal power uprate level may be obvious to the utility (for example, if only one scenario results in the MWe level that is needed to support increased demand; if only one scenario includes a positive return on investment; if only one scenario results in acceptable risk in accordance with company guidelines). However, in other cases, there may not be one scenario that can be easily identified as the optimal power uprate level. This report aims to provide a tool to help utilities identify the optimal power uprate by visualizing differences in various power uprate scenarios considering traditional risk and financial elements, but also the company's motivation for nuclear, which is often not being consciously considered in the process.

To use this tool, a company first evaluates the power uprate scenarios using traditional financial and risk evaluations. Each scenario is then given an individual financial score and risk score using guidance that is provided in Tables 3-3 and 3-4; **higher financial scores and lower risk scores are desirable**. The company's motivation for nuclear is then factored in by calculating a sliding-scale weight factor for the risk portion of the power level assessment considering the current landscape. This factor is referred to herein as the *risk tolerance weight factor*. The general premise behind the risk tolerance weight factor is that utilities that are more motivated for additional nuclear power would have a higher risk tolerance (and subsequently would be more likely to consider higher power uprate levels). The factor is calculated by evaluating a series of criteria associated with (1) company objectives and (2) market forecast, as follows:

- *Company objectives* pertains to how a company views nuclear as part of its generation portfolio and how motivated it is to achieve climate goals. It answers the question: How much does the utility value nuclear production? This element is scored in accordance with guidance provided in Table 3-5.
- *Market forecast* refers to the company's projected outlook for the energy market and its demand for nuclear. This element is scored in accordance with guidance provided in Table 3-6.

These two scores are summed and correlated to an associated risk tolerance weight factor using guidance provided in Table 3-7. A higher motivation score equates to higher risk tolerance; so, the risk tolerance weight factor should lower the overall risk score. As Table 3-7 shows, the risk tolerance weight factor is inversely related to the motivation score—that is, higher motivation score equates to lower risk tolerance weight factor. This risk tolerance weight factor is multiplied to the risk score of each power uprate scenario, ultimately lowering the overall risk score and giving more emphasis to the financial score. The financial score and risk score can then be plotted against a heat map, providing a visual for how financially viable and risky each power uprate scenario is. A heat map template is provided in Figure 3-1 for reference. The ideal option would have a high financial score and a low risk score. Utilities can then decide which power uprate is

optimal by leveraging this tool in concert with existing utility processes using traditional financial and risk assessments. At the end of this step, plant personnel will have identified the optimal power uprate level to pursue.

Note that the tool is provided as a baseline for utilities to augment as needed. Utilities may want to include additional metrics (for example, customer rate impact) or change some of the scoring criteria to better suit their specific goals (for example, NPV metrics for revenue goals). Utilities may also decide on scaling differently the risk tolerance weight factor in accordance with existing company processes or even adding a weight factor on the financial score.

Table 3-3
Financial analysis matrix key

Score	NPV	Payback Period	Levelized Cost of Electricity (LCOE)
1 Minimum	$NPV \leq 0$	$t > 12$ years	Power uprate will significantly raise plant LCOE over expected operating lifetime.
2 Low	$\$0M < NPV \leq \$50M$	$9 < t \leq 12$ years	Power uprate will raise plant LCOE over expected operating lifetime.
3 Average	$\$50M < NPV \leq \$100M$	$6 < t \leq 9$ years	Power uprate has negligible impact on plant LCOE over expected operating lifetime.
4 High	$\$100M < NPV \leq \$200M$	$3 < t \leq 6$ years	Power uprate will lower plant LCOE over expected operating lifetime.
5 Maximum	$NPV > \$200M$	$t \leq 3$ years	Power uprate will significantly lower plant LCOE over expected operating lifetime.

Each column should be ranked individually from 1 to 5, giving a total score ranging from 3 to 15 for financial analysis.

Table 3-4
Risk assessment matrix key

Score	Regulatory/Implementation	Component Replacement Enterprise	Project Execution
5 Maximum	Power uprate level is beyond all historical industry limits.	Project has at least eight or more individual projects within the overall power uprate project portfolio that would be considered an enterprise risk project.	There is no clear path to staff the project.
4 High	Power uprate level is beyond historical limits for similar make and model industry peers.	Project has at least six individual projects within the overall power uprate project portfolio that would be considered an enterprise risk project.	Project staffing expected to include resources with limited experience on plant knowledge, large modifications, and/or power uprates.
3 Average	Power uprate level is at or below historical limits for similar make and model industry peers.	Project has at least four individual projects within the overall power uprate project portfolio that would be considered an enterprise risk project.	Project staffing expected to include some personnel with experience on plant knowledge, large modifications, and/or power uprates but not for any key roles (for example, project manager, responsible engineers).
2 Low	SPU.	Project has at least two individual projects within the overall power uprate project portfolio that would be considered an enterprise risk project.	There are commitments from resources including personnel with experience on plant knowledge, large modifications, and/or power uprates to fill some but not all key roles.
1 Minimum	MUR.	Project has no individual projects within the overall power uprate project portfolio that would be considered an enterprise risk project.	There are commitments from resources including personnel with experience on plant knowledge, large modifications, and/or power uprates to fill all key roles.

Each column should be ranked individually from 1 to 5, giving a total score ranging from 3 to 15 for risk assessment.

Table 3-5
Company objectives scoring matrix

Score	Additional Nuclear Generation	Remaining Plant Operating Life	Climate Goals
1 Minimum	Company has completely ruled out pursuing additional nuclear generation.	Company plans to operate existing nuclear assets for 10 years or less.	Company has no climate-related goals.
2 Low	Company has no plan to add nuclear generation.	Company plans to operate existing nuclear assets for 10–20 years.	Company has weak climate-related goals.
3 Average	Company is contemplating additional nuclear generation.	Company plans to operate existing nuclear assets for 20–30 years.	Company has some climate-related related goals.
4 High	Company has initiated study for additional nuclear generation.	Company plans to operate existing nuclear assets for 30–40 years.	Company has strong climate-related goals.
5 Maximum	Company is actively pursuing additional nuclear generation.	Company plans to operate existing nuclear assets for over 40 years.	Company's main priorities are climate-related goals.

Each column should be ranked individually from 1 to 5, giving a total score ranging from 3 to 15 for company objectives.

**Table 3-6
Market forecast scoring matrix**

Score	Demand for Nuclear Generation	External Support ¹	Beyond Electricity Opportunities
1 Minimum	No forecasted demand for nuclear generation in region.	No national, state/province, or regional support for NPPs	No beyond electricity opportunities (for example, hydrogen production) in region
2 Low	Forecasted demand for nuclear generation in region is below current demand.	Weak national, state, or local support for NPPs	Limited beyond electricity opportunities in region
3 Average	Forecasted demand for nuclear generation in region equals current demand.	Some national, state, or local support for NPPs	Some beyond electricity opportunities in region
4 High	Forecasted demand for nuclear generation in region is above current demand.	Good national, state, or local support for NPPs	Many beyond electricity opportunities in region
5 Maximum	Forecasted demand for nuclear generation in region is significantly above current demand	Very strong national, state, or local support for NPPs	Company already pursuing beyond electricity options

Each column should be ranked individually from 1 to 5, giving a total score ranging from 3 to 15 for market forecast.

¹ Support includes government/politicians, utility districts, communities, unions, and other stakeholders.

**Table 3-7
Scoring matrix weight factor**

Motivation Score ¹	Risk Tolerance Weight Factor ²
6 to 10	1.0
11 to 15	0.9
16 to 20	0.8
21 to 25	0.7
26 to 30	0.6

¹ Motivation score is calculated by summing company objectives and market forecast scores.

² Risk tolerance weight factor values provided herein are baseline values, which may be adjusted based on utility-specific risk tolerance.

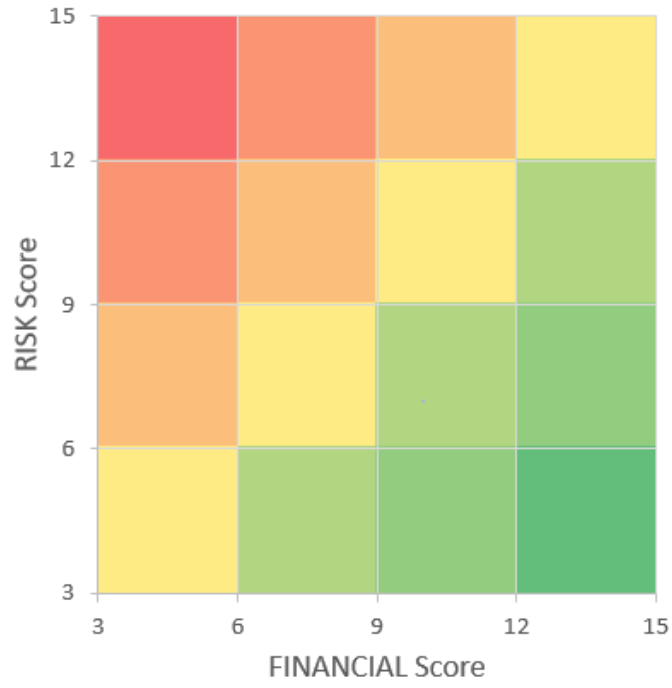


Figure 3-1
Financial and risk heat map template

4

DETAILED GUIDANCE FOR POWER UPRATE INITIAL DECISION-MAKING PROCESS OPTIMIZATION

This section provides detailed steps for generating the potential power uprate range and selecting the optimal power uprate level as part of the initial decision-making step of the overall power uprate process. Specifically, it elaborates on the discussion for Steps 1–5 of the optimized initial decision-making process covered in Section 3.2. These five steps are shown in Figure 4-1. Example tables and figures provided in this section serve as examples of the output from each step. These examples are provided to support implementation of the guidance.

It is noted that the guidance presented in this section is intended to support a feasibility study rather than a detailed technical evaluation (see Section 1.4).

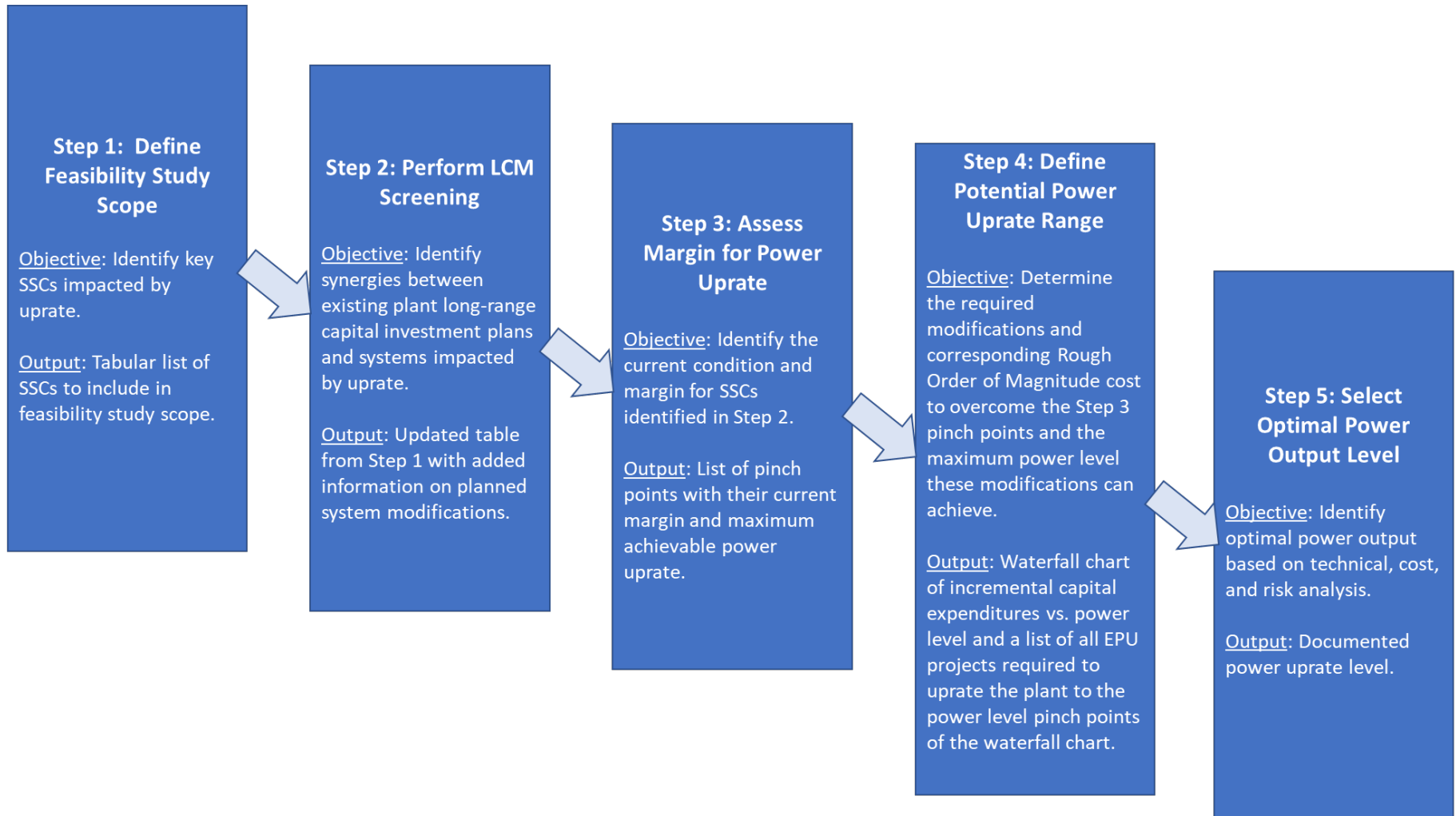


Figure 4-1
Feasibility study process

4.1 Define Feasibility Study Scope

Plant personnel should perform the following steps to fully define the feasibility study scope (It is recommended that the collected information be documented in a power uprate feasibility study table, an example of which is shown in Table 4-1.):

1. List all major plant systems.
2. List all plant programs (this includes environmental protection programs and permits).
3. List all safety analyses.
 - A. Review plant licensing documents (for example, updated final safety analysis report for U.S. plants) to obtain a comprehensive list of all safety analyses.
 - B. Review fuel analyses to identify impact on safety analysis limits.
4. Review regulatory standards or guidance for power uprate to understand the regulator's review scope and confirm that the systems, programs, and safety analyses in the power uprate review scope are included in the list from Steps 1, 2, and 3—for example, Sections 1 and 2 of NRC RS-001 [14] for U.S. plants.
5. Identify plant systems that will be significantly affected by a power uprate.
 - A. Factors to consider for uprate impact are capacity, reliability, and efficiency.⁷ Specifically:
 - i. Potential that the system impacts nuclear safety or generation (for example, failures in the system have historically resulted in significant generation loss for the unit and/or the broader fleet of similar reactor style). Safety analyses can be leveraged in this step to reveal key SSCs that may require modification to satisfy existing acceptance criteria.
 - ii. Systems, safety analyses, or programs that have been historically problematic for the plant are known to be single point vulnerabilities or are expected to require a significant investment to ensure reliable operation of the plant through end of plant life. Note that, although program owner responsibilities may not be impacted by power uprate, a programmatic review may reveal components that have recurring issues and result in component pinch points. A list of typical programs is provided in Table 3-2.
 - B. Compare systems with those of Table 3-1 to ensure that the key systems typically affected by power uprate have been considered. Table 3-1 lists typical key systems impacted by power uprate. This list was generated through industry OE (for example, plant personnel surveys and publicly available documentation such as power uprate requests for additional information and Safety Evaluation Reports).

⁷ An example of an impact on capacity is when the uprate requires a pump output beyond what the OEM recommends. An example of an impact on reliability is the need to use a spare feedwater pump during normal operation at uprated power because this will reduce redundancy. An example of an impact on efficiency is the pump operating further away from its BEP, which could ultimately result in reduced component life.

6. Using the identified plant systems that will be significantly affected by a power uprate, identify the corresponding major plant structures and components impacted by power uprate (see Step A.1 of Appendix A for an example).
 - A. Major plant components are those components whose upgrade/replacement would require significant investment (for example, \$1M or more).
 - B. Impacted plant components are those components that must increase performance (for example, increased pump flows) to support the power uprate. Impacted plant components are also components that, if the performance is adversely impacted by a power uprate, could result in accelerated degradation or prevent the system from meeting its functions (for example, resulting in potential scram, limiting condition for operation).
 - C. **Example:** For the condensate system, the major plant components typically include the condenser, condensate pump, condensate booster pump, steam jet air ejector, condensate demineralizer, and low-pressure FWHs. Note that plants may categorize some of these components in separate, or stand-alone, systems (for example, main condenser).
 - D. Solicit inputs from system and program owners, safety analysis leads, and any SMEs who have had significant experience with plant power uprates and major modifications for this screening activity.
 - E. Include the rationale for each structure and component that screens in as a significant uprate impact—for example, increased heat duty.
7. When the list of SSCs is generated, confirm with owners and experienced plant personnel that the list is comprehensive.
 - A. Owners should consider the current plant performance and flag any known SSC issues because existing challenges are typically exacerbated with power uprate.
 - B. It is recommended to also engage with major plant OEMs (for example, nuclear steam supply system, turbine generator, steam generator) to confirm that the list of SSCs is appropriate.
8. Conduct an OE review (for example, NRC Event Reporting, INPO IRIS Database) to identify plant components with key vulnerabilities. The OE search may help identify additional pinch points for the plant. Owners should use search terms relevant to the list of SSCs generated in this step along with *uprate*.
9. Add any new SSCs from Steps 4.1.7 through 4.1.8 to the feasibility study table.

At the end of this step, plant personnel will have a list of all SSCs that are expected to be significantly impacted by a power uprate. See Table 4-1 for an example feasibility study table.

Table 4-1
Example feasibility study table, after Step 4.1

	Item	Owner/Lead	Significant Uprate Impact? ¹ (Y/N)	Rationale
System 1	Pump A	Engineer A	Y	Increased system flow
	HX A	Engineer B	Y	Increased heat duty
	...	---	---	---
	Component n	---	---	---
System 2	Pump A	Engineer C	Y	Increased system flow
	...	---	---	---
	Component n	---	---	---
...	...	---	---	---
System n	HX A	Engineer D	Y	Increased heat duty
	...	---	---	---
	Component n	---	---	---

HX = heat exchanger

¹ A significant uprate impact for a system is an upgrade/replacement as a result of the uprate that will require an investment of \$1M or more.

4.2 Perform LCM Screening

The following steps should be performed to identify the plant component modifications or replacements that are, or should be, included in the plant LRP so that (1) the scope of the margin assessment (Section 4.3) is fully defined and (2) existing LCM costs can be understood and synergized with potential power uprate modifications or replacements:

1. Review the current plant list of planned capital projects (that is, LRP) as a basis for understanding current and/or future projects for the in-scope systems identified in Step 4.1.
2. Determine the planned operating lifetime to be considered for the uprate feasibility assessment and whether the LRP includes planned modifications through the expected plant operating lifetime or a meaningful time frame for which LRP projects will impact power uprate strategy (for example, 10 years past power uprate implementation). For example, if a utility intends to pursue SLR, the required upgrades to operate the plant through the second period of extended operation should be included in the LRP.

3. Interview plant personnel (for example, system engineers, supervisors, operations) to identify additional planned LCM projects that may be required through plant lifetime that are not currently on the LRP. Questions should focus on the following aspects:
 - A. Are there any prior LCM studies to determine whether there are other projects to add to the LRP?
 - B. Are there known but unfunded projects that are not on the LRP?
 - C. Is there information from existing component LCM plans that should be included in the LRP?
 - D. Are there time-based projects that are expected to occur during the plant lifetime that are not on the LRP?
 - E. Are there current material condition issues (for example, documented in system health reports or condition reports) that could drive a future replacement project?
 - F. Is the system challenged during particular seasons at rated power where LCM modifications could result in additional generation?
 - G. Are there equipment obsolescence concerns considering the plant operating lifetime (for example, with SLR)?
4. Review any relevant documentation identified by plant personnel interviews (for example, condition reports) to confirm interview findings.
5. Using the results of the above steps, identify the LCM projects (and rough order of magnitude [ROM] costs) that may be necessary to reach end of plant life, independent of power uprate.
6. Update the feasibility study table generated in Step 4.1 with the relevant LCM projects for a given component, along with target implementation date.⁸ It is also important here to flag which LCM project timelines may need to be accelerated to coordinate with the power uprate implementation timeline.

An example table with LCM data is shown in Table 4-2, with the shaded columns indicating the changes from Table 4-1.

At the end of this step, plant personnel will have identified the SSCs with LCM projects that impact power uprate strategy. SSCs without LCM projects for planned upgrades/replacements identified in Step 4.1 will be evaluated for margin in Step 4.3.

⁸ Collaboration between LCM plan owners and power uprate project personnel is necessary during the power uprate project to ensure that changes in LCM and power uprate strategy are timely communicated to prevent gaps in uprate implementation.

Table 4-2
Example feasibility study table, after Step 4.2 (added columns in gray)

	Item	Owner/Lead	Significant Uprate Impact? ¹ (Y/N)	Rationale	Planned LCM Upgrade/Replacement? (Y/N)	LCM Project (ID and Description)	LCM Project Implementation Year
System 1	Pump A	Engineer A	Y	Increased system flow	Y	LCM.1—replace pump	2024
	HX A	Engineer B	Y	Increased heat duty	Y	LCM.2—retube HX	2026
	...						
	Component n						
System 2	Pump A	Engineer C	Y	Increased system flow			
	...	---	---	---			
	Component n	---	---	---			
::	...	---	---	---			
System n	HX A	Engineer D	Y	Increased heat duty			
	...	---	---	---			
	Component n	---	---	---			

HX = heat exchanger

¹ A significant uprate impact for a system, program, or evaluation is an upgrade/replacement as a result of the uprate that will require an investment of \$1M or more.

4.3 Assess Margin for Power Uprate

The following steps should be completed to assess plant margin for power uprate:

1. For the key SSCs flagged from Step 4.2, identify critical parameters that control/affect performance and will be adversely impacted by power uprate.

Example: Critical parameters for a motor-driven pump are net positive suction head (NPSH), flow capacity/total dynamic head (TDH), BEP, and motor power output.

2. For each of the critical parameters, identify the following, as applicable:
 - A. Current operating parameter at full power and any additional limiting system conditions. If actual operating point is not known, identify the design point.
 - B. The operating limit.
 - C. The TS limit.
 - D. The analyzed design limit.

It is expected that the following inputs will be necessary to complete this step:

- Inputs from plant personnel to gain understanding of operational and analytical challenges with current power (for example, degradation of existing plant systems, known plant vulnerabilities).
 - Current plant operating data (for example, plant condition reports) to characterize actual system performance. Plant operating data need to include summer and winter conditions, as well as all plant modes of operation.
 - Design and licensing bases for nuclear steam supply system and BOP SSCs.
 - Emergency, alarm response, and normal operating procedures.
 - Thermal kit, vendor datasheet, vendor manual, analytical models, and plant heat balance to confirm that existing system performance is consistent with expected performance.
3. Determine the power level at which a component parameter limit is reached and, therefore, a pinch point occurs.

In some uprate feasibility studies, the power uprate lead has convened expert panels consisting of plant personnel, nuclear steam supply system vendors, and major equipment OEMs to assess equipment and safety analysis margins. It is good practice to engage these stakeholders at this point in the feasibility study to assist in determining pinch points.

4. Request that SMEs, owners, and experienced plant personnel review power level pinch points identified for each SSC. Specifically, discuss any underlying health issues that could limit the achievable power uprate that are not evaluated in Step 4.3.3, and ensure that the conditions that were used for the margin assessment are indeed limiting.

At the end of this step, plant personnel will have a list that includes (1) the current margin for key SSC parameters and (2) the maximum power uprate that can be accommodated for a given parameter as currently designed. Table 4-3 is provided as an example.

Additionally, plant personnel should anticipate that some of the operating and TS limits may be impacted by a power uprate. Because this is a feasibility study for power uprate and not a detailed study, it is sufficient to identify limits that may be affected by power uprate conditions, as shown in Table 4-3, for operating and TS limits.

Table 4-3
Example margin assessment table⁹

	Item	Critical Parameter	Current Operating Conditions	Operating/Test Limit	Operating Limit Impacted by Uprate? (Y/N)	TS Limit	TS Limit Impacted by Uprate? (Y/N)	Design Limit	Maximum Power Uprate (CLTP)	Comments
System 1	Pump A	NPSH	48 ft	40 ft	Y	N/A	N	35 ft	137% ¹	N/A
		BEP	100%	N/A	N	N/A	N	120%	120%	N/A
		TDH	600 ft	N/A	N	N/A	N/A	N/A	N/A	Need sufficient head for the desired flow rate
		Flow rate	2750 gpm	N/A	N	N/A	N/A	N/A	N/A	
		Motor output power	550 bhp	N/A	N	N/A	N	560 bhp	106%	N/A
	Component 2	Crit. Param. 1								
		Crit. Param. N								
	Component n									
System n	Component 1									
	Component n									

1 ft = 0.3 m 1 gpm = 3.7854 lpm

¹ Maximum power uprate is assumed to increase proportionally as the NPSH current operating condition approaches the design limit.

⁹ Table 4-3 is adapted for power uprate from the table in INPO 09-003[3].

4.4 Definite Potential Power Uprate Range

The following steps should be completed to define the potential power uprate range:

1. Using Table 4-3, create a table of SSCs that will need to be modified or replaced to support further increase in power. An example table is provided in Table 4-4. The table should also include a qualitative (that is, low, medium, high) assessment of the degree of certainty in the power uprate level at which the modification is required. Additionally, the table should include the following:
 - A. Impact on plant safety margins
 - B. Impact on plant reliability (including near-term and long-term impacts)
 - C. Environmental concerns and/or seasonal limitations
 - D. Potential for scope increase
 - E. Potential for nonconservatism in margin
 - F. Schedule confidence
 - G. Budgetary confidence
 - H. Regulatory risks (for example, licensing, permitting)
 - I. Procurement challenges and supply chain interruptions
2. For each SSC of Table 4-4, develop a list of potential modification strategies to overcome the limitation and the maximum power level that the modification can support.
 - A. Start with SSCs that will drive the upper bound of the potential power due to their low margin, high cost, long lead, and the potential technical limitations of sizing replacement components. These SSCs include the main generator, main turbine, steam dryer (BWR), main condenser, moisture separators reheaters, and steam generator (PWR).
 - B. Potential modification options should consider component interdependency—that is, margin may be recaptured in a component by upgrading other component(s) in the system or connected systems (for example, condensate pumps, condensate booster pumps, feedwater pumps).
 - C. Plant personnel should ensure that any modifications to SSCs address all parameters that result in the pinch point.

Appendix A provides an example using this guidance for various modifications associated with the condensate system.
3. Confirm that a replacement or upgrade is feasible for the maximum identified power level for components that were not evaluated in the margin assessment due to existing LCM projects (see Step 4.2).

4. For each modification option, obtain a ROM¹⁰ cost.
 - A. Potential sources for ROM costs include (1) similar projects conducted at the plant, (2) industry OE, and/or (3) vendor input.
 - B. At this stage, it is not necessary to obtain a detailed cost-estimate; however, the costs should skew conservative to account for future unknowns (for example, volatility of material costs).
 - C. Modification costs should be separated into LCM cost and incremental power uprate cost where there is an existing LCM project for a component that overlaps with the power uprate modification. Incremental power uprate costs are power uprate modification costs beyond those projected from the LCM plan.
5. Using Table 4-4, develop a waterfall chart that depicts incremental power uprate cost as a function of potential power level. An example waterfall chart is shown in Figure 4-2.
 - A. The waterfall chart is a visual way to show the potential power uprate range and various power uprate scenarios that need to be analyzed when selecting the target power level for uprate. For simplification, it is recommended to group projects that have similar power uprate levels (for example, within 1%) at which the modification is required.
 - B. Different modifications may allow an SSC to achieve different power levels, and the modification that is ultimately selected depends on the desired power uprate. For example, modification option 1 may permit operation up to 105% CLTP, whereas modification option 2 is required to uprate above 105% CLTP. As a result, the appropriate modification depends on what power level is desired.

It will be useful for the plant to develop multiple waterfall charts to visually represent the investments needed to exceed a given power level. However, it is recommended that additional waterfall charts be limited to high-cost modifications to limit the number of waterfalls generated as part of the feasibility study. Alternatively, a single waterfall plot can be generated to show the cost at 102% power and the incremented cost at 105% (that is, the difference between the cost of the modifications to exceed 102% and 105% CLTP).

At the end of this step, plant personnel will have (1) a power uprate project table that includes a list of all significant projects broken down by SSCs, ROM costs broken down by LCM (if there is an existing project independent of power uprate), *incremental* power uprate cost, the power level at which a given modification is required, and the level of confidence in the power level at which a given modification is required (see Table 4-4) and (2) a waterfall chart that depicts the potential power uprate scenarios (see Figure 4-2).

¹⁰ A ROM estimate is, by definition, a Level 5 cost estimate as documented by the American Association of Cost Engineering [15].

The example waterfall chart shown in Figure 4-2 indicates the following:

- The plant requires a \$75M investment to operate up to 106% CLTP.
- With an additional \$250M investment, the plant can operate up to 112% CLTP.
- For an additional \$75M, the plant can operate up to 116% CLTP.
- For an additional \$175M, the plant can operate up to 130% CLTP.
- Total investment of \$575M to achieve 130% CLTP.

Table 4-4
Example power uprate project table

Item	Project	ROM for LCM Cost	ROM for Incremental Power Uprate Cost	Power Level at which Modification is Required ¹	Level of Confidence ² in Power Level (H/M/L)
System 1, Pump A	Project 1.a	N/A	\$250M	106% CLTP	High
System 1, HX A	Project 1.b	N/A	\$75M	112% CLTP	High
System 2, MSR A	Project 1.c	N/A	\$175M	116% CLTP	Medium
System 2, HX B	Project 1.d	N/A	\$75M	100% CLTP	High

HX = heat exchanger MSR = moisture separator reheater

¹ This is the maximum power uprate level the existing component can tolerate. Modification is required to achieve a higher power level.

² This is qualitative assessment of the degree of certainty in the power uprate level at which the modification is required.

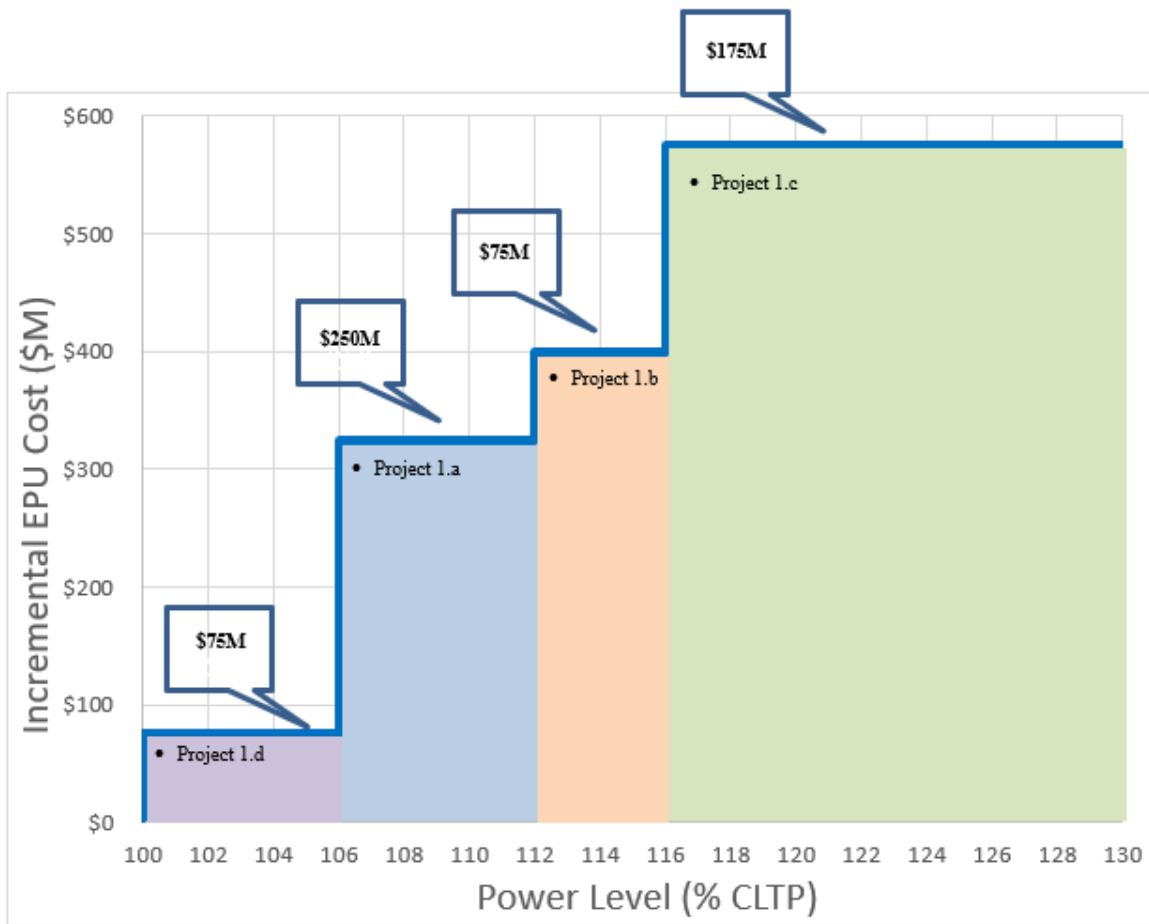


Figure 4-2
Example waterfall chart

4.5 Select Optimal Power Uprate Level

The following steps should be completed to select the optimal power uprate level (As noted in Section 3.2.5, utilities may want to revisit the criteria, scoring, and weighting for their specific sites.):

1. Perform a financial analysis for each scenario leveraging existing utility processes.
 - A. Build or incorporate power uprate into existing company or industry financial models.
 - i. Include in the model the **incremental** capital costs due to power uprate that have been identified in Step 4.4.
 - ii. Estimate **incremental** fuel costs for each uprate scenario working with fuels group.

- iii. Estimate any **incremental** additions or reduction in operations and maintenance (O&M) costs as a result of power uprate. O&M incremental costs can be estimated as none because the component replacements, which (1) reduce and/or reset maintenance activities and (2) increase component reliability, are expected to offset increases in O&M costs (for example, increased FAC costs).
 - iv. Include outage duration impact for implementing power uprate modifications in the financial model.
 - v. Consider overall plant strategy (that is, plant operating lifetime, financing decisions), as well as findings from regional power studies (for example, future power pricing) in the model.
 - B. Assign a score in accordance with Table 3-3 for NPV, payback period, and LCOE from the business model for each scenario.
 - C. Sum the score for each of the three elements (NPV, payback period, and LCOE) to obtain a total financial score for each scenario.
2. Perform a risk assessment for each scenario using existing utility processes.
- A. Identify differences in each scenario in relation to regulatory/implementation risks, enterprise project risks, and project execution risks, and assign a score for each using Table 3-4 for each scenario.
 - B. Sum the score for each of the three elements to obtain a total risk score for each scenario.
3. Determine a motivation score for each scenario.
- A. Determine a score for the company's nuclear power objectives.
 - i. Review recently published business plans if available. These plans typically provide insights about utility's business goals/strategy with ongoing and future key initiatives (for example, to meet climate goals).
 - ii. Conduct high-level management and executive interviews to align on business goals/strategy for new nuclear, license renewal, and climate goals. It is recommended to review how the motivation score is calculated to identify the elements that factor into the calculation of the motivation score.
 - iii. Assign a score in accordance with Table 3-5 for additional nuclear generation, plant operating life, and climate goals.
 - iv. Sum the score for each of the three elements to obtain a total company objectives score.
 - B. Determine a score for market forecast of nuclear power in the region.
 - i. Review all regional and federal incentives (for example, state regulations, energy bills).
 - ii. Use prior studies or perform a new regional study to determine region's future demand for firm, carbon-free power.

- iii. Conduct high-level management and executive interviews and research external opportunities for beyond electricity (for example, hydrogen production) applications. It is recommended to review how the market forecast score is calculated to identify the elements that factor into the calculation of the market forecast score.

This step should be combined with Step 4.5.3.A.ii to make interviews efficient.

- iv. Assign a score in accordance with Table 3-6 for demand, external support and beyond electricity.
- v. Sum the score for each of the three elements to obtain a total market forecast score.

C. Sum the scores from Steps 4.5.3.A and 4.5.3.B into a single motivation score.

- 4. Determine the subsequent risk tolerance weight factor using Table 3-7. An example is shown in Table 4-5.
- 5. Multiply the risk tolerance weight factor with the total risks core for each scenario to determine an updated Risk score.
- 6. Plot the subsequent total financial score and updated total risk score for each scenario on a heat map to visualize each scenario.
- 7. Determine the optimal power uprate level using the results of this tool, the detailed financial and risk assessments, and existing plant processes and procedures.

An example of how to document the preceding steps for three different power uprate scenarios is provided in Table 4-5. Figure 4-3 provides an example of the power heat map for the same three scenarios.

Table 4-5
Power uprate level selection table example

Attribute	Rating Guidelines	Score		
		Scenario 1	Scenario 2	Scenario 3
Financial Analysis				
NPV	Table 3-3	2	3	5
Payback period	Table 3-3	5	3	2
LCOE	Table 3-3	3	3	4
Total FINANCIAL score		10	9	11
Risk Analysis				
Regulatory/implementation	Table 3-4	3	3	4
Component replacement enterprise	Table 3-4	2	3	4
Project execution	Table 3-4	2	3	4
Total RISK score		7	9	12
Risk Tolerance				
Company Objectives				
Additional nuclear generation	Table 3-5	3		
Plant operating life	Table 3-5	4		
Climate goals	Table 3-5	3		
Subtotal for category		10		
Market Forecast				
Demand	Table 3-6	4		
External support	Table 3-6	3		
Beyond electricity	Table 3-6	3		
Subtotal for category		10		
Risk Tolerance Weight Factor				
Motivation score	Table 3-7	20		
Weight risk factor	Table 3-7	0.8		
Updated total RISK score		5.6	7.2	9.6

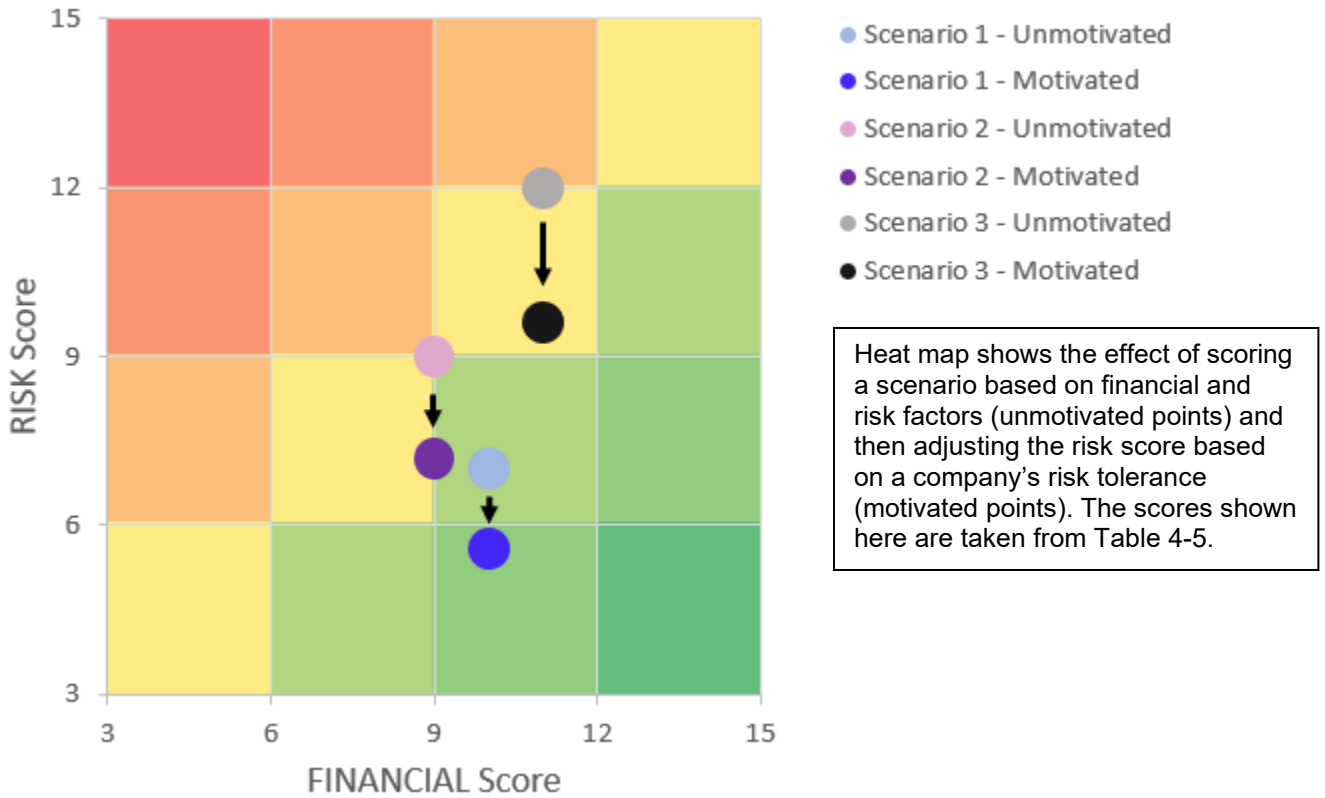


Figure 4-3
Example power uprate heat map

5

SUMMARY

Upgrading a NPP is a cost-effective and reliable way to add base-load, carbon-free power to the electrical grid while meeting aggressive climate goals. The present favorable economic conditions coupled with the intrinsic value of nuclear in meeting climate goals have created the opportunity to upgrade plants to power levels beyond those previously achieved, challenging how the nuclear industry perceives hard stops to power upgrades.

That considered, power upgrades remain in most instances complex projects that can lead to significant overruns and technical issues post-implementation, if not properly planned and executed. One of the first steps of the power upgrade project is the feasibility study during which an optimal power upgrade is selected.

Existing guidance on this step is limited and high level. This report provides a systematic approach with detailed steps to optimize future upgrade projects and ultimately reduce overall risks. This optimized guideline specifically includes considerations, such as (1) the intrinsic value of nuclear in meeting climate goals, (2) the synergy of an upgrade with existing LCM projects, and (3) plant operational strategy (for example, SLR), that are not included in current guidance.

The guidance and process in this report were developed by building upon historical guidance and experience and inputs from utilities, OEMs, nuclear steam supply system vendors, specialty engineering companies, and other nuclear industry stakeholders.

Executing the process found within this report will help nuclear utilities determine the maximum technically achievable power upgrade and provide utility leadership options for choosing the optimum upgrade considering the plant overall strategy, energy market, business case, and risks.

6

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A

CONDENSATE SYSTEM

This appendix provides an example for performing the system evaluation and can be followed for other systems. This specific example focuses on the condensate system, which has been historically affected by power uprate. Section A.1 provides the impact of the power uprate on the key components of the condensate system, typical issues, and potential modifications to recover margin. Section A.2 covers one additional strategy considering the overall plant. Lastly, Section A.3 summarizes the findings of this appendix into a concise table.

A.1 Power Uprate Impact

A.1.1 Key System Components

The following are the key condensate system components, along with their design function:

- **Condenser.** Condense low-pressure turbine exhaust steam and maintain turbine backpressure.
- **Condensate pumps.** Increase condensate pressure to drive through system components and supply sufficient suction pressure to feedwater pumps.
- **Condensate booster pumps.** Provide additional energy to increase condensate system pressure prior to the feedwater pumps.
- **Vacuum pump/steam jet air ejector.** Remove noncondensables from the condenser to maintain turbine backpressure.
- **Demineralizer or filter demineralizer.** Remove impurities (for example, corrosion products) from the system to prevent collection in the steam generator or reactor.
- **Low-pressure feedwater heaters (FWHs).** Increase the thermal efficiency of the cycle by heating condensate using turbine extraction steam prior to entering the steam generator or reactor.

The increase in condensate flow rate following power uprate can challenge operation of all key components of the condensate system at the uprated power. The main component impacts are summarized as follows (Subsequent sections cover the impacts of power uprates on key system components that should be evaluated for plant power uprate pinch points.).

- With the higher flow rate, condensers can be subject to flow-induced vibrations (FIVs) due to the increased turbine exhaust flow and excessively high back pressure.
- For pumps, two main considerations are their capacity to pump the increased flow rate with the adequate head and sufficient NPSH.

- For the demineralizers, the main considerations during a power uprate are (1) capacity to efficiently remove impurities at the higher flow velocity and temperature and (2) the demineralizer's backwash or resin regeneration activities (for example, increased frequency). For BWRs, plant personnel must also consider the additional strain on radwaste operations (for example, resin processing).
- The FWHs' concerns include their ability to transfer the required heat at higher power, their ability to pass the increased cascade drain flow, their compatibility with the pressure/temperature post-uprate, and FIV.

The following sections provide details for evaluating these components at a selected power level. The sections explain how to (1) conduct the margin assessment at the current power level, (2) identify the maximum power at which each of these components can operate, and (3) highlight the potential solutions to restore margin if any of these components are identified as pinch points.

A.1.2 Condenser

The condenser condenses steam from the low-pressure turbines by circulating cold water in the tube side of the condenser. The circulating water takes suction either from a cooling tower basin (closed-loop cooling) or directly from a lake, river, or ocean (once-through cooling). The performance of the condenser is, therefore, dependent on the performance of the circulating water system, and these two must be evaluated together to explore all potential options to recover condenser performance margin.

The condenser has been flagged as a pinch point for power uprates, because many utilities are already operating near the condenser design limits. This is especially true for units that have a cooling tower, because the condenser inlet cooling water temperature (that is, circulating water temperature) is high during high wet bulb temperature days and these units had to derate from time to time to prevent excursions above the back-pressure limits on the turbines.

The typical evaluations for condensers are those for FIV, steam erosion, and thermal performance, summarized as follows:

- For the thermal performance, the condenser must be able to adequately perform under the increased heat duty while maintaining acceptable backpressure.
 - Thermal performance of the condenser can be derived by hand or software (for example, HTRI, PEPSE).
 - The larger load on the condenser increases the condenser backpressure, which in turn reduces margin against various setpoint trips (for example, low-pressure vacuum, high temperature off-gas isolation). These need to be evaluated to prevent plant trips due to exceeding plant setpoints, which was a frequent occurrence during the early stages of power uprates.
 - The evaluation should consider various cleanliness levels and circulating water temperatures.
- Increases in steam flow velocity can result in steam erosion on the shell, tubes, and supports.

Utilities can elect to upgrade their condenser or circulating water system to overcome pinch points. Table A-1 shows options to recover margin for the condenser.

**Table A-1
Condenser power uprate modification strategies**

Power Uprate Evaluations	Modification Strategy	Change on Component or System	Description
Thermal performance limitation	Tube bundle replacement	Component	<p>Tube bundles can be replaced with larger capacity by increasing surface area and/or selecting higher conductive tube material.</p> <p>This modification is quite expensive and is typically the last resort to upgrade the condenser.</p>
	Retubing	Component	The condenser can be retubed to recover margin from plugged tubes.
	Modular condenser replacement	Component	A modular condenser with larger capacity could be used to replace an existing condenser.
	Circulating water pump upgrade	System	<p>By increasing the circulating water mass flow rate, the condenser removal heat duty may be increased (depending on the plant condenser and operating conditions).</p> <p>This strategy should consider the impact of increased circulating water velocity in the tubes. There must also be considerations for the impact of higher mass flow rate on other components of the circulating water system (for example, valves).</p> <p>This option may also require the plant to revise the water permit to increase discharge flow and/or temperature.</p>
	Upgrade of cooling tower	System	<p>There are many options to upgrade natural draft cooling towers. The most common upgrades are as follows:</p> <ul style="list-style-type: none"> • Add an auxiliary mechanical draft cooling tower. • Repair/upgrade peripheral fill to improve flow distribution system and add fill layers in key locations. • Replace cooling tower with new fiberglass model. • Change crossflow to counterflow tower.
	Increase in water discharge temperature	System	Utilities may need to submit a licensing or environmental permit approval request to increase the circulating water discharge temperature.
FIV	Tube staking	Component	This strategy consists of installing tube stakes to reduce excessive tube vibration.
	Tube support addition	Component	This strategy consists of adding tube supports so that the maximum tube support span prevents FIV or modular tube bundle replacement.
Steam erosion	Condenser retrofit	Component	Tube erosion could be addressed by changing tube material or adding/enlarging impingement plates. Shell and support erosion can be addressed by local reinforcement modifications or replacement.

A.1.3 Condensate System Pumps and Motors

The following sections identify the key parameters for condensate system pumps and motors. The parameters will need to be evaluated for current margin and assessed for impact from power uprate. The outputs of these evaluations will determine at what point the pump or motor becomes a pinch point that requires a significant investment to further increase plant power.

A.1.3.1 NPSH Evaluation

During the feasibility study, the margin between the available NPSH and the vendor-required NPSH for the range of operating conditions will be identified.

Typically, NPSH is not an issue for standard vertical pumps because these pumps are designed to operate with low available NPSH and some cavitation. As such, vertical pumps are not typically considered for NPSH evaluation. For high-suction energy pumps, Hydraulic Institute standards recommend that the pump available NPSH exceed the required NPSH by a factor of 2.5. Therefore, utilities will assess how much margin there is between the available and required NPSHs considering a 2.5 safety factor.

The maximum flow rate that the pump can handle while maintaining sufficient margin against NPSH can be derived by assuming a linear reduction in NPSH margin with power level for the condensate system.

A.1.3.2 Low-Suction Pressure Evaluation

Pump suction pressure at the uprated power level must be evaluated so that suction pressure does not drop below the acceptable limit during all plant operating modes. Alarms and setpoints can be found in plant documentation whereas the suction pressure is typically obtained from plant operating data. The ratio of this suction pressure and alarm setpoint indicates the margin for the low-suction pressure evaluation.

A.1.3.3 BEP Evaluation

Typically, pumps can accommodate the desired higher flow rate while operating near BEP (typically between 70% and 120% of the BEP flow for centrifugal pumps and vertical pumps with specific speeds greater than 4500 rpm [Hydraulic Institute standards]). Assuming a linear increase in flow rate with power, the new pump operating point can be assessed for a given uprate level. Utilities should ensure that the ratio of the operating point to the BEP remains within the acceptable range from the vendor.

A.1.3.4 Motor Power Rating Evaluation

A key parameter for pumps is the motor power rating (kW and HP) and whether this rating is sufficient for the increased pump power demand. The motor power demand can be determined by using the pump brake horsepower curve while assuming a linear increase in mass flow rate for a given power level.

A.1.3.5 Pump Pinch Point Modification Strategies

If any of the parameters noted previously exceed margin in the range of power uprate levels evaluated, the pump is a pinch point. Table A-2 lists typical strategies to overcome the pinch point. In lieu of the options listed in Table A-2, pump replacement can be pursued.

**Table A-2
Pump power uprate modification strategies**

Pump Evaluations	Strategy	Change on Component or System	Description
Insufficient capacity to pump required amount of flow with adequate head	Impeller modification	Component	<p>Utilities could either replace pump impeller with a larger impeller or underfile the pump impeller. Both options provide more favorable head flow curve as long as the pump shaft, casing, and motor can accommodate this pump upgrade. Underfiling impellers may result in less flow stability, which should be carefully considered.</p> <p>This type of strategy is typically sufficient if there is not much margin to recover (a small percentage).</p>
	Additional/spare pump	System	<p>Plants can leverage their additional spare pumps (for example, condensate pump, if available) to continue operating near the BEP at the uprated power level. This option will also help restore downstream pumps' NPSH margin.</p> <p>The downside of this option is that it reduces plant redundancy so that the plant will be more sensitive to trip with the loss of a pump.</p> <p>If the condensate pump is the pinch point, a spare pump or a condensate booster pump could be leveraged to increase the required flow and TDH. If a new pump is added, the space constraint is usually the limiting factor for this strategy (that is, new piping routing, electrical wires, and so forth).</p>
	Upgrade motor (if limiting)	Component	<p>Motor winding temperature is typically limiting. If the motor rating is not sufficient, plants must replace the motor with a larger capacity. This strategy should consider the additional electrical loading on the AC/DC system.</p>
	Reduced downstream pressure loss	System	<p>This strategy consists of upgrading other pinch points and select designs with reduced pressure loss to reduce the required TDH of the pumps (for example, FWH pressure loss for the condensate pumps). Alternatively, plants can also investigate whether they can open valves even more if these are fairly restrictive (for example, feedwater regulating valves for PWRs, and so forth).</p>

Table A-2 (continued)
Pump power uprate modification strategies

Pump Evaluations	Strategy	Change on Component or System	Description
Insufficient NPSH	Low NPSHR impeller	Component	To recover NPSH margin, one can modify the impeller design with a low NPSHR impeller. This modification may result in a bigger impeller eye, which will impact the BEP, and ultimately reduce the acceptable range of operation.
	Pump suction water level	System	This strategy consists of raising the pump suction water level (for example, condenser hotwell level) to increase the pressure at the pump suction. This strategy should be discussed with operators to confirm that it does not impinge on operating transient margins. This strategy may not be feasible for some plants/systems but is worth considering if the margin to recover is small.
	Lower pump suction Intake	Component	Lowering the pump suction intake will increase the static suction pressure. This strategy may be feasible for only a few plants/systems but is worth considering if the margin to recover is small.
	Reduced upstream pressure loss	System	If upstream pressure loss can be reduced (for example, open valve more), the suction pressure of the pump will increase.

AC/DC = alternating current/direct current

A.1.4 Vacuum Pump/Steam Jet Air Ejector

Depending on the plant design and operating conditions, power uprate may result in an increased load on the equipment that maintains condenser vacuum, such as due to increased radiolytic decomposition of hydrogen and oxygen. Vacuum equipment capacity should be assessed at the uprated condition to determine whether modifications are necessary. Modifications are typically replacement with increased capacity equipment and may require additional replacement of supporting equipment (for example, steam control valves).

A.1.5 Demineralizers

The condensate system relies on several condensate demineralizers or filter demineralizer vessels to remove the impurities in its water. The flow through each vessel is controlled by regulating effluent discharge valves. Typically, utilities can operate with one of the vessels out of service to accommodate online backwash and resin regeneration. Each vessel can tolerate only a certain flow rate, above which performance is impacted. There is also a temperature limit to maintain adequate water chemistry.

To address flow limitations through existing vessels, utilities have several options (see Table A-3).

Table A-3
Demineralizer power uprate modification strategies

Power Uprate Evaluations	Modification Strategy	Change on Component or System	Description
Flow limitation	Additional vessel	Component	Utilities can add a vessel if space allows to reduce the flow velocity through the existing vessels and ensure that it remains below acceptable level.
	New skid	Component	A new skid would consist of a new vessel, valves, piping, and control components to augment or replace the existing system. The advantage of a new skid is that it can address flow limitations, control obsolescence, and backwash equipment concerns.
	Bypass line	System	The bypass line will support backwash during high power operation.

Regardless of the option, because BWR demineralizers are contaminated, the modification will have to consider demineralizer location to minimize exposure during installation.

A.1.6 Low-Pressure FWHs

FWHs increase plant cycle efficiency by preheating condensate. Extraction steam is routed from various turbine stages to the FWHs, where the steam energy is used to increase condensate temperature. The extraction steam condenses and typically cascades through lower pressure heaters to the condenser.

Power uprate will increase the mass flow on both the tube and the shell side of plant FWHs. This can cause increased tube, shell, and nozzle wear rates and increased tube vibrations and tube wear. The critical FWH parameters to evaluate when assessing the equipment for power uprate implementation include the following:

- Tube side
 - Nozzle velocity
 - Tube velocity
 - Pressure drop
 - Design pressure and temperature
 - FIV from increased shell-side flow over tubes
- Shell side
 - Steam inlet nozzle velocity
 - Drain inlet nozzle mass flux
 - Drain nozzle velocity
 - Design pressure and temperature

The acceptability of these parameters at power uprate conditions can be assessed using Heat Exchange Institute standards.

Table A-4 provides modification strategies to overcome pinch points and recover FWH margin.

Table A-4
FWH power uprate modification strategies

Power Uprate Evaluations	Modification Strategy	Change on Component or System	Description
Flow limitation	Additional FWH string	System	Utilities can add an additional series of FWHs in parallel with the existing FWH strings to reduce flows through individual FWHs.
	FWH bypass line	System	Bypassing FWHs reduces the flow rate through individual FWHs. This option reduces plant thermal efficiency.
	Tube sleeve	Component	Tube sleeves would regain margin for plugged tubes and mitigate the increase tube erosion and vibration wear from increased steam and tube-side flow rates.
	Shell or shell section replacement/reinforcement	Component	FWH shell replacement/reinforcement provides additional margin for FWH shell thinning.
	Impingement plate modification	Component	Steam erosion on FWH tubes can be mitigated by installation of impingement plates.
	Nozzle replacement	Component	Should nozzle velocities and increased wear rates be of concern, steam, tube-side, and cooler nozzles could be replaced and resized for the increased flow rates.
Design temperature/pressure/limitation	Rerate FWH	Component	Analyses to rerate FWHs to accommodate power uprate conditions should be performed.
Thermal performance limitation	FWH replacement or tube bundle replacement	Component	FWH or tube bundle should be replaced to be compatible with power uprate conditions (Note that replacing a tube bundle to address thermal performance limitation may require modifications to extend the shell if a significant increase in heat transfer area is required.).

A.2 System Strategy

In addition to the component-specific strategies to address pinch point, this section identifies an additional strategy to reduce the demand and restore margin.

A.2.1 Conversion of Heater Drains to Forward Pumped

At least one plant surveyed considered redesigning the heater drain system to be a forward pumped system. A forward pumped system is a configuration in which the condensate of the heater drains is pumped forward to rejoin the main condensate line, rather than cascading to a lower stage FWH or draining to the main condenser. This would be a major modification and would include (1) installing larger heater drain tanks, heater drain pumps, and large bore piping and (2) replacing FWH level control valves, among other modifications. This system change would reduce the flow rates (and associated pressure drops) in the condensate system, which would restore condensate pump and filter demineralizer margin. Additionally, this system design could reduce flow rate through level control valves for the low-pressure FWHs at the uprated power level. A forward pumped heater drain system could be considered by plants as an option to address multiple condensate system pinch points provided that there is sufficient space to accommodate such a large modification.

A.3 Summary for Condensate System

Table A-5 summarizes the impacts of power uprate, issues, and potential resolution strategies related to the condensate system.

**Table A-5
Condensate system power uprate system impacts and potential modification strategies**

Component	Power Uprate Impact	Potential Issue	Resolution Strategy
Condenser	Increased heat duty	Insufficient thermal performance	<ul style="list-style-type: none"> • Retube condenser • Replace tube bundle • Replace condenser • Upgrade circulating water pumps • Upgrade cooling tower • Revise permit
	Increased mass flow rate on shell side	FIV leading to tube wear/damage	<ul style="list-style-type: none"> • Stake tubes • Add tube support(s) • Replace condenser
		Steam erosion of tube and shell components	<ul style="list-style-type: none"> • Perform condenser retrofit (for example, modify or add impingement plates)
Pumps (condensate and condensate booster)	Increased mass flow rate	Insufficient capacity to pump required amount of flow with adequate head (that is, low feedwater pump suction pressure)	<ul style="list-style-type: none"> • Replace pump • Modify impeller with larger impeller or underfile impeller • Use spare condensate pump • Add or use spare booster pump • Upgrade motor (if limiting) • Reduce downstream pressure loss
		Insufficient NPSH	<ul style="list-style-type: none"> • Replace pump • Replace impeller with low NPSHR impeller • Increase condenser hotwell water level • Lower pump suction • Reduce upstream pressure loss

Table A-5 (continued)
Condensate system power uprate system impacts and potential modification strategies

Component	Power Uprate Impact	Potential Issue	Resolution Strategy
Vacuum pump/steam jet air ejector	Increased condenser noncondensable load	Loss of vacuum and condenser performance	<ul style="list-style-type: none"> • Replace with increased capacity equipment.
Demineralizer (or filter demineralizer)	Increased mass flow rate	Flow velocity exceeding vendor recommendation impacting performance	<ul style="list-style-type: none"> • Replace demineralizer • Add vessel • Add new skid • Add bypass line
Low-pressure FWHs	Increased mass flow rate	Increased wear rates and lost performance	<ul style="list-style-type: none"> • Replace FWH • Add FWH string • Add FWH bypass line • Replace tube sleeves • Replace/reinforce FWH shell or shell section • Install impingement plate • Replace nozzles
	Increased temperature and pressure	Temperature and pressure exceeds design conditions	<ul style="list-style-type: none"> • Rerate FWH
	Increased heat duty	Insufficient thermal performance	<ul style="list-style-type: none"> • Replace FWH • Replace tube bundle (may require extension of the shell due to increased area)
Multiple	Increased flow rate	Multiple	<ul style="list-style-type: none"> • Add heater drain pump forwarding system (significant system modification, see Section A.2.1)

B

FEASIBILITY STUDY TEMPLATE

This appendix provides a template for creating the feasibility study report according to the guidance in Section 4. This appendix is not intended to be a comprehensive example of the feasibility study; rather, it serves as a framework that will be expanded upon for the actual feasibility study report.

This appendix lists the general sections that would be expected in a feasibility study report (for example, executive summary, introduction, and so forth). Within each section there is generic guidance on the type of content to include in the section. *The text in these sections is italicized to indicate that it is guidance for content.*

Executive Summary

The executive summary should provide the key takeaways from the feasibility study. The executive summary should equip senior management and executives with the information to determine whether continuing to pursue a power uprate is the correct path forward and, if so, specify the optimal power level. The executive summary should include the following:

- *Purpose of the study*
- *Background (brief description of relevant plant information, plant uprate history, license status, plant overall strategy, and motivation for the power uprate)*
- *Brief description of the feasibility study scope and methodology*
- *Recommended power uprate level and the total investment needed*
- *Brief justification for selecting the recommended power uprate level*
- *Any significant risks that have been identified*

The executive summary should conclude with a brief description of recommended next steps.

B.1 Introduction

B.1.1 Purpose

This section should succinctly describe what this feasibility study seeks to accomplish.

B.1.2 Background

The background section should provide relevant plant information that will help the reader contextualize what will come later in the report. This can include the following:

- *Background information about plant*
- *History of plant power uprates (including those pursued but not implemented)*
- *License status (remaining years)*
- *Plant overall strategy (for example, SLR intent)*
- *Motivation for power uprate (that is, the basis for considering power uprate now)*

B.1.3 Approach for the Feasibility Study

This section should outline the methodology used for completing the feasibility study. Sections 3 and 4 of this report can be used as the framework for this section. Other items to include in this section are the following:

- *Key vendors supporting the assessment and their scope*
- *Assumptions and approaches used when defining the scope and depth of the study (for example, where the boundary is between the grid operator and the plant, modification cost estimation process)*

This section could also summarize the key elements of the approach used for this power uprate feasibility study including the following:

- *Define feasibility study scope: Identify key systems, structures, and components (SSCs) impacted by uprate by considering the potential for impact on capacity, reliability, and efficiency or the potential cost of replacement.*
- *Perform LCM screening: Identify which of the key impacted SSCs have existing plant long-range capital investment plans. Impacted SSCs with planned modifications or replacements are not evaluated for existing margin because they will be resized to accommodate the optimal power level.*
- *Assess margin for power uprate: Evaluate the existing margin at current operating conditions for the SSCs that are impacted by power uprate and do not have a planned modification or replacement. The existing margin will dictate the maximum power uprate level each key SSC can tolerate before requiring modification.*
- *Define potential power uprate range: Determine the rough order of magnitude (ROM) for the cost of modifying each key SSC to achieve a power level beyond the maximum it can tolerate in its current state. Reconcile the estimated LCM costs for the SSCs identified in the LCM screening to determine the incremental cost of power uprate.*
- *Select target output level: Identify the optimal level of power uprate based on technical, financial, and risk analysis.*

B.2 Feasibility Study Results

The template herein follows the steps of Section 4.0. The preparer of the report may elect to combine sections as appropriate (for example, to avoid redundancy in the feasibility study). When writing the section of the feasibility report, the preparer should focus on the key takeaways, significant issues, cost, and reliability impacts, as opposed to a thorough description of the results.

B.2.1 Systems, Structures, and Components Impacted by Power Uprate

This section documents the results of Section 4.1, which are the SSCs that were determined to be affected by power uprate and require significant investment to modify, thereby requiring further assessment of available margin. This section provides a high-level summary of the results and any general conclusions. A table will be developed and included in Appendix 1 to document these key SSCs affected by power uprate. Table 4-1 should be used as a template.

B.2.2 SSCs Addressed in LCM Plans

This section documents the results of Section 4.2, which evaluates the key SSCs affected by power uprate that are in LCM plans.¹¹ This section provides a high-level summary of the results and any general conclusions. A table will be developed and included in Appendix 2 of this feasibility study to document these key SSCs impacted by power uprate that have planned LCM replacements. Table 4-2 should be used as a template.

B.2.3 SSCs Margin Analysis

This section documents the results of Section 4.3 by summarizing the key takeaways from the component margin evaluations (for example, components with negative margin or low margin). The margin assessment table used to identify pinch points will be developed and included in Appendix 3 of this feasibility study. Table 4-3 should be used as a template.

B.2.4 Potential Power Uprate Range

This section documents the results of Section 4.4 by identifying modification strategies to overcome component pinch points determined in the margin assessment and provide estimates of the costs associated with each modification strategy. Using the margin assessment table and the estimated LCM and/or power uprate modification costs, a table will be developed that identifies the maximum power level that can be achieved by each unmodified component. The table will also include the estimated LCM and/or power uprate modification costs to exceed the existing component's maximum power level (that is, overcome the pinch point). Table 4-4 should be used as a template. A waterfall plot will be generated using the table.

Given the size of the table, the margin table should be documented in an appendix of the feasibility study.

¹¹ LCM plans can also be referred to as *asset management, aging management, continued operation, long-term operations, or LRPs*.

B.2.5 Optimal Power Uprate Selection

This section documents the results of Section 4.5. The methods, assumptions, and inputs used to select the power uprate level are covered. Specifically, this section covers the financial analysis and risk assessment for each power uprate scenario along with the motivation to pursue power uprate considering internal objectives and market forecast. A table will be generated to score each power uprate scenario according to the guidance of Section 4.5 and assist in generating a heat map that can help selecting the optimal power uprate.

B.3 Conclusions and Recommendations

This section summarizes key aspects of the feasibility study. A single power uprate scenario is recommended, and the basis for recommendation is covered. This section should include the following:

- *Optimal power uprate level*
- *Total investment and basis*
- *Key project risks*
- *Next steps for power uprate implementation, which may include the following:*
 - *Developing power uprate project organization structure and project schedule*
 - *Defining project communication plan, risk strategy, procurement strategy, and quality requirements*
 - *Contracting vendors to perform safety analyses at the selected power level*

A table should be provided to show the full list of projects and estimated costs to achieve the selected power level.

B.4 Appendices

This section lists all of the appendices of the feasibility study (for example, appendix that includes the margin assessment table).

C

EXAMPLE FEASIBILITY STUDY: BUZZARDS BEACH NUCLEAR POWER PLANT POWER UPRATE FEASIBILITY STUDY

Executive Summary

Current economic and social conditions (for example, aggressive climate goals) have provided a strong driver to maximize the generation from zero-carbon emission energy sources. Based on these favorable market conditions and the inherent plant design margin, power uprate is being considered for Buzzards Beach Nuclear Power Plant (NPP). A power uprate feasibility study was performed to determine the optimal power uprate level.

Buzzards Beach NPP is an approximately 1000-MWe nuclear facility in the northeastern region of the United States. The plant entered commercial operation in 1990 and was approved for first license renewal in 2018. It is likely that the plant will pursue subsequent license renewal (SLR). The plant has not undergone any power uprates in its history, which provides an opportunity to increase the power generation while also meeting demanding state climate goals.

The feasibility study identified five potential power uprate scenarios across a potential power uprate range from 106% to 134% of current licensed thermal power (CLPT), as depicted in Figure C-1. Figure C-1 (known as the *waterfall chart*) provides the power uprate level percentage and associated costs to achieve that power level.

From the five scenarios considered, the optimum power uprate for Buzzards Beach NPP was identified as 34% of CLTP (~340 MWe) at an estimated cost of approximately \$1B considering existing life-cycle management costs and incremental power uprate costs. This power level was selected considering company objectives, market forecasts, risk assessments, and financial analyses. Implementing this power level will result in large capital costs and enterprise level risks. There is also limited operating experience (OE) in increasing power level to that extent for such a plant design. However, the technical and risk assessments performed as part of this feasibility study (including inputs from nuclear steam supply system and BOP component original equipment manufacturers [OEMs]) identified no hard stops that would preclude safe and reliable operation of the plant at this power level. Further, this additional capacity will assist in filling the future projected need in firm carbon-free power in the state.

Next step for Buzzards Beach NPP is to perform key alternative analyses for Projects 5a, 6b, 8a, and 9a, which were associated with complex modifications and/or long lead items. This effort will help refine the rough order of magnitude (ROM) and scope of work for the power uprate.

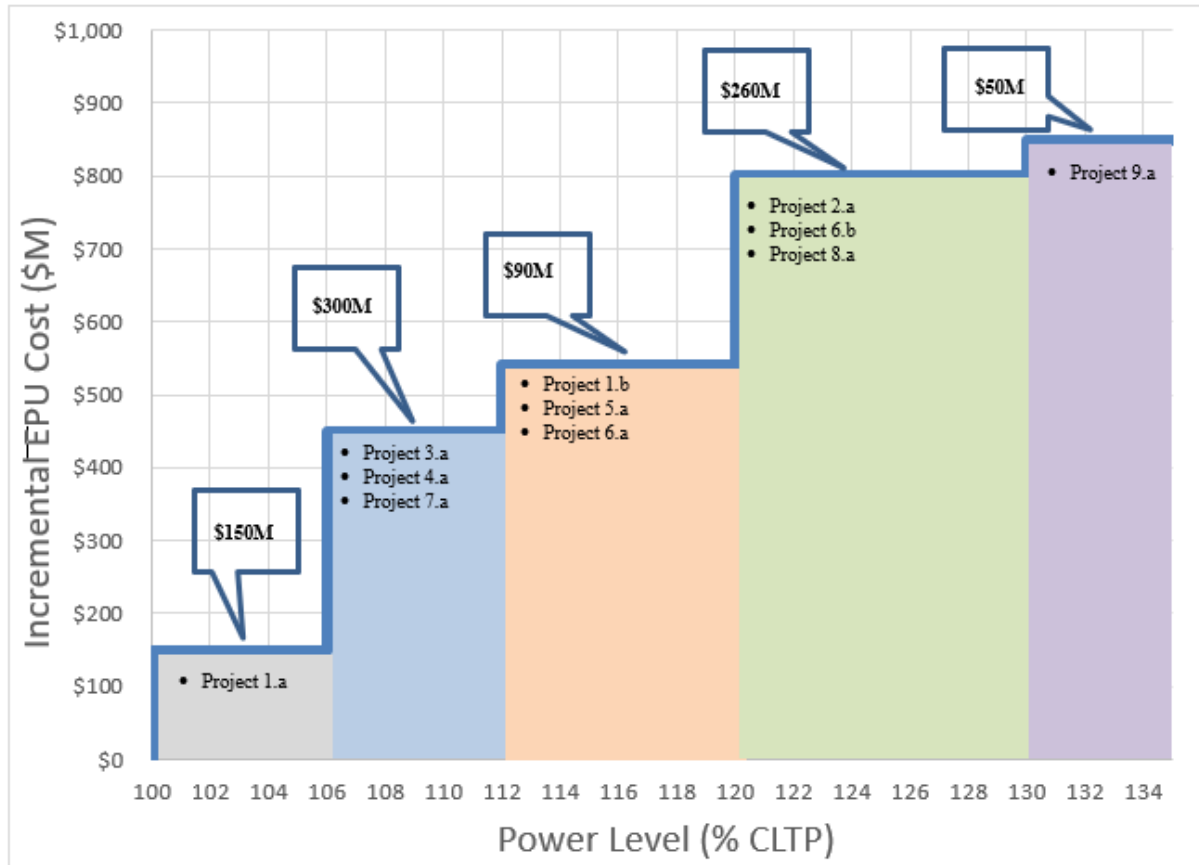


Figure C-1
Power uprate waterfall chart

C.1 Introduction

C.1.1 Purpose

The purpose of this feasibility study is to identify the optimal uprate scenario for Buzzards Beach NPP by (1) identifying the major components that would require significant investment for a power uprate, (2) identifying their available design margin, potential modifications, risks, and associated cost if the design margin were to be exceeded due to a power uprate, and (3) reconciling potential power uprate modifications with anticipated life-cycle management (LCM) efforts to determine the incremental cost of power uprate. Current economic and social conditions provide favorable incentives for optimizing the output of NPPs. Increasing the zero-carbon emission energy output of NPPs will support country, state, region, province, and Buzzards Beach NPP owner/operator (Buzzards Beach Nuclear Operating Company) goals associated with climate and reducing carbon emissions.

C.1.2 Background

Buzzards Beach NPP entered commercial operation in 1990 and has not undergone any power uprates in its history; it is still at its originally licensed power level. The NPP has operated efficiently and safely over the course of its lifetime and was approved for license renewal in 2018.

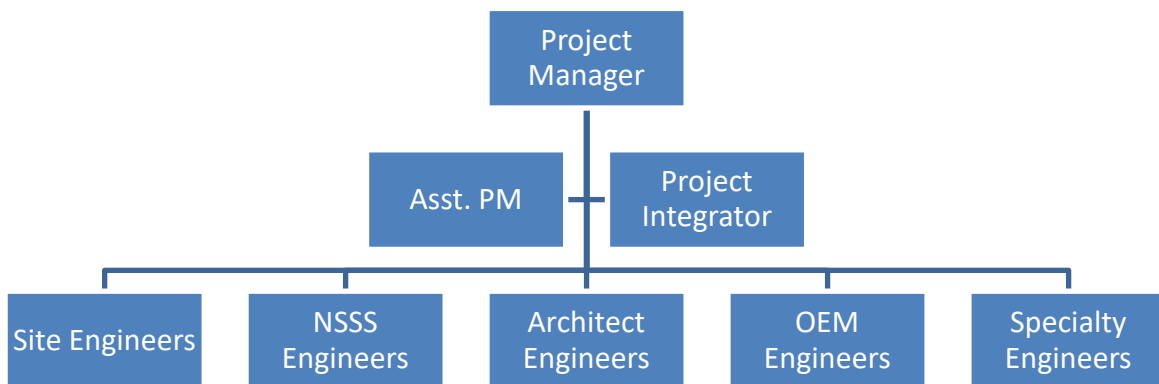
Power uprate for the plant is now being considered due to the favorable national and regional nuclear market conditions, Buzzards Beach Nuclear Operating Company's prioritization of expanding its nuclear generation output, and the inherent margin in the NPP design. It is expected based on the plant performance and industry licensing trends that Buzzards Beach NPP will be seeking a SLR (that is, operating for at least 80 years), thereby increasing the time for return on investment of power uprate.

C.1.3 Approach

The feasibility study followed the process from EPRI report 3002026402, *Facilitating Power Uprates at Nuclear Power Plants*. The approach is a five-step process, which entails the following:

1. Defining the feasibility study scope
2. Performing a LCM screening
3. Assessing margins for power uprate
4. Defining the potential power uprate range
5. Selecting the optimum power output level

A project manager and project team were identified to lead the effort. Key members of the project organization are shown in Figure C-2.



NSSS = nuclear steam supply system

Figure C-2
Feasibility study project organization

C.2 Results

The results are summarized in the following sections, which correspond to the five steps of the feasibility study process identified in the preceding Approach section. The working file used to generate the tables presented in this study are contained in an Excel spreadsheet.

C.2.1 Systems, Structures, and Components Scoping Table

Starting with a comprehensive list of plant systems, programs, and safety analyses, SSCs that are affected by power uprate and expected to require a significant investment to modify are shown in Table C-1.

Appendix 1 shows the full list of SSCs that were considered when determining which components are significantly impacted by power uprate. Only those for which power uprate was considered a significant impact are shown in Table C-1.

Table C-1
Key SSCs impacted by power uprate for example feasibility study

	Item	Rationale for Power Uprate Impact
Condensate System	Condensate booster pumps	Increased system flow
	Main condenser	Increased heat duty
	Condensate filter demineralizer	Increased system flow, increased operating temperatures
	Low-pressure feedwater heaters	Increased heat duty, increased system flows
Main Steam	Moisture separator reheater	Increased system flows, increased operating temperatures
	Relief valves	Increased system flow
	MSIVs	Increased system flow
	Main generator	Increased power output
	Steam generator	Increased heat duty, increased system flow

MSIV = main steam isolation valve

Table C-1 is for example only. The actual feasibility study report table would include more SCC entries.

The table can be removed from the main body of the feasibility study if too long.

C.2.2 LCM Screening Table

Table C-2 identifies the components from Table C-1 that have LCM plans in place—that is, these components that already have planned capital modifications to sustain operation at the current thermal power level for the remainder of the current license. These components were excluded from the margin assessment in the next step because these components are already being upgraded and system engineers confirmed that these components could be designed to the target output power level at no cost or small incremental cost.

Appendix 2 shows the full table generated as part of the LCM screening performed in this step. Only components from Appendix 2 that have an identified LCM plan are shown in Table C-2.

Table C-2
Impacted SSCs addressed by existing LCM plans for example feasibility study

	Item	Owner/Lead	Rationale for Power Uprate Impact	LCM Project (ID and Description)	LCM Project Implementation Year
Main Steam	Moisture separator reheater	Engineer D	Increased system flows, increased operating temperatures	LCM-01: MSR New Chevron Design	2026
	Main generator	OEM	Increased power output	LCM-06: Stator Rewind	2025

Table C-2 is for example only. The actual feasibility study report table would have many more SSC entries.

C.2.3 SSC Margin Analysis

The margin assessment table developed for this step in the analysis is provided in Appendix 3. The margin assessment covers these SSCs that are significantly impacted by power uprate but do not have a planned LCM upgrade or replacement.

C.2.4 Potential Power Uprate Range

Based on the margin assessment table, SSCs that require modifications to exceed a given power uprate were identified, along with the full suite of expected modifications and LCM upgrade or replacement projects for each SSC. Specifically, Table C-3 identifies the maximum power level that can be achieved by each unmodified component and provides the estimated LCM and/or power uprate modification costs to exceed that power level. Costs are delineated between LCM costs and power uprate modifications costs; so, the incremental cost of a power uprate is determined.

The waterfall chart in Figure C-3 shows the incremental power uprate cost to achieve a given power uprate level. At 134% CLTP, Buzzards Beach NPP identified a hard stop.

Note that this section should also include key conclusions from the margin assessment table. These are not included in this example.

Table C-3
Example power uprate project table

Item	Project	ROM for LCM Cost	ROM for Incremental Power Uprate Cost	Power Level at which Modification is Required ¹	Level of Confidence ² in Power Level (H/M/L)
System 1, SSC A	Project 1.a	N/A	\$150M	100% CLTP	High
System 1, SSC B	Project 1.b	\$60M	\$40M	112% CLTP	High
System 2, SSC A	Project 2.a	N/A	\$60M	120% CLTP	Medium
System 3, SSC A	Project 3.a	N/A	\$95M	106% CLTP	Low
System 4, SSC A	Project 4.a	N/A	\$80M	106% CLTP	Medium
System 5, SSC A	Project 5.a	\$25M	\$30M	112% CLTP	High
System 6, SSC A	Project 6.a	N/A	\$20M	112% CLTP	High
System 6, SSC B	Project 6.b	N/A	\$50M	120% CLTP	High
System 7, SSC A	Project 7.a	N/A	\$125M	106% CLTP	High
System 8, SSC A	Project 8.a	N/A	\$150M	120% CLTP	Medium
System 9, SSC A	Project 9.a	\$50M	\$50M	130% CLTP	Medium

¹ This is the maximum power uprate level that the existing component can tolerate. Modification is required to achieve a higher power level.

² This is a qualitative assessment of the degree of certainty in the power uprate level at which the modification is required.

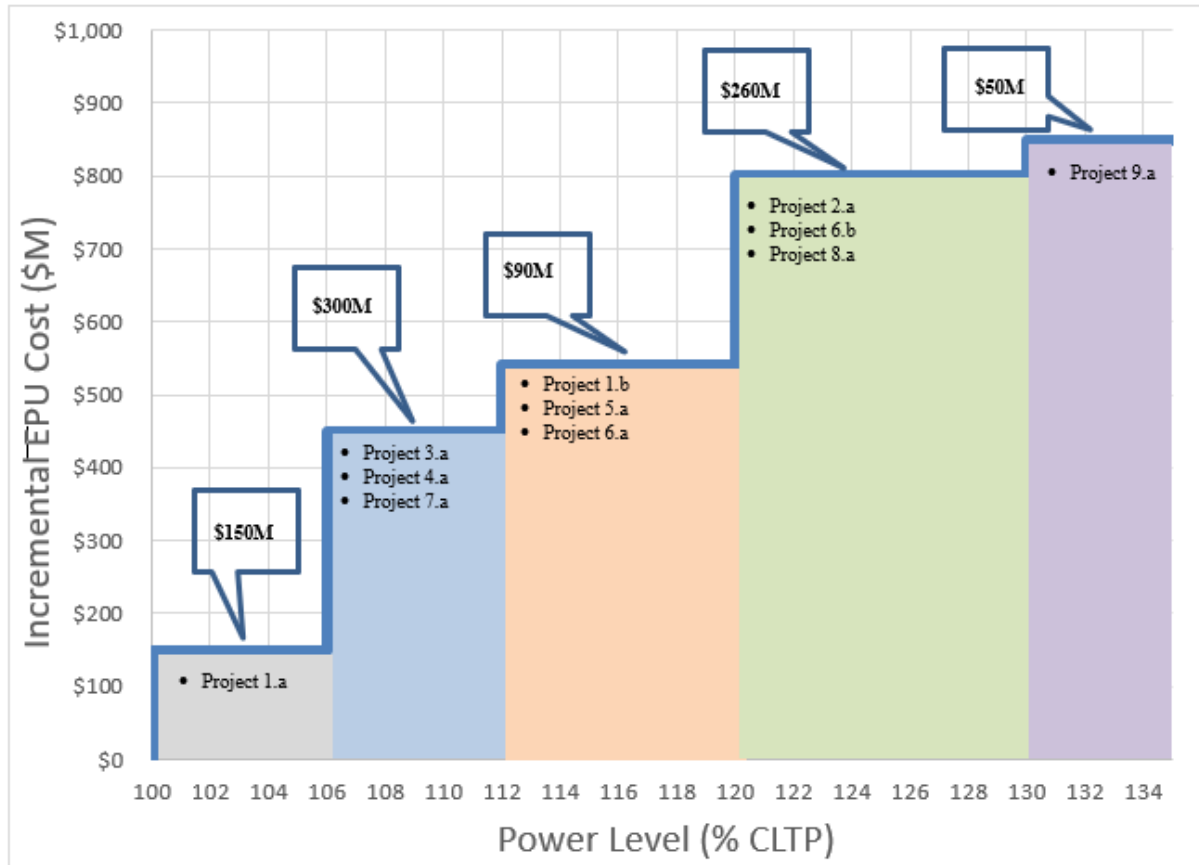


Figure C-3
Power uprate waterfall chart

C.2.5 Optimal Power Uprate Selection

Table C-4 provides financial and risks scores to quantify how financially viable and risky each of the power uprate considered is. Table C-4 also includes a motivation score, which quantifies how much Buzzards Beach NPP values nuclear generation in the current landscape. This motivation score is then converted into a risk tolerance weight factor that is used to adjust the risk score, the rationale being that utilities that are more motivated for additional nuclear power would have a higher risk tolerance (and subsequently would be more likely to consider higher power uprate levels). The resultant scores are plotted on a heat map to help visualize each of the five options with and without consideration for Buzzards Nuclear NPP’s motivation. The heat map is provided in Figure C-4.

As expected, Figure C-4 indicates that the risk level increases with power uprate level. The financial score, however, varies depending on the return on investment (NPV, LCOE, and payback period). For example, Figure C-4 shows that Scenario 1 (106% of CLTP) is low risk and financially attractive, but it increases power generation by 6%, which is well below the utility needs.

Scenario 5 (134% of CLTP) results in large enterprise level risks and capital costs, but this scenario still remains financially attractive when considering NPV, LCOE, and payback period. There is also limited OE in increasing power level to that extent for such a plant design. However, the technical and risk assessments performed as part of this feasibility study (including inputs from nuclear steam supply system and BOP component OEMs) identified no hard stops that would preclude safe and reliable operation of the plant at this power level. Further, this additional capacity will assist in filling the future projected need in firm carbon-free power in the state and meet the utility's climate goals. Based on the above, 134% CLTP is selected as the optimal uprate level for Buzzards Beach NPP.

Table C-4
Power level selection table

Attribute	Rating Guidelines	Scenario 1 106% CLTP	Scenario 2 112% CLTP	Scenario 3 120% CLTP	Scenario 4 130% CLTP	Scenario 5 134% CLTP
		Score	Score	Score	Score	Score
Financial Analysis						
NPV	Table 3-3	3	2	4	3	5
Payback period	Table 3-3	4	2	3	3	3
LCOE	Table 3-3	4	2	4	4	5
Total FINANCIAL score		11	6	11	10	13
Risk Analysis						
Regulatory/implementation	Table 3-4	2	3	3	5	5
Component replacement enterprise	Table 3-4	1	2	3	4	5
Project execution	Table 3-4	2	3	3	4	4
Total RISK score		5	8	9	13	14
Risk Tolerance						
Company Objectives						
Additional nuclear	Table 3-5	3				
Plant operating life	Table 3-5	4				
Climate goals	Table 3-5	3				
Subtotal for category		10				
Market Forecast						
Demand	Table 3-6	4				
External support	Table 3-6	3				
Beyond electricity	Table 3-6	3				
Subtotal for category		10				
Weight Factor						
Motivation score	Table 3-7	20				
Weight risk factor	Table 3-7	0.8				
Total RISK score with weight factor		4	6.4	7.2	10.4	11.2

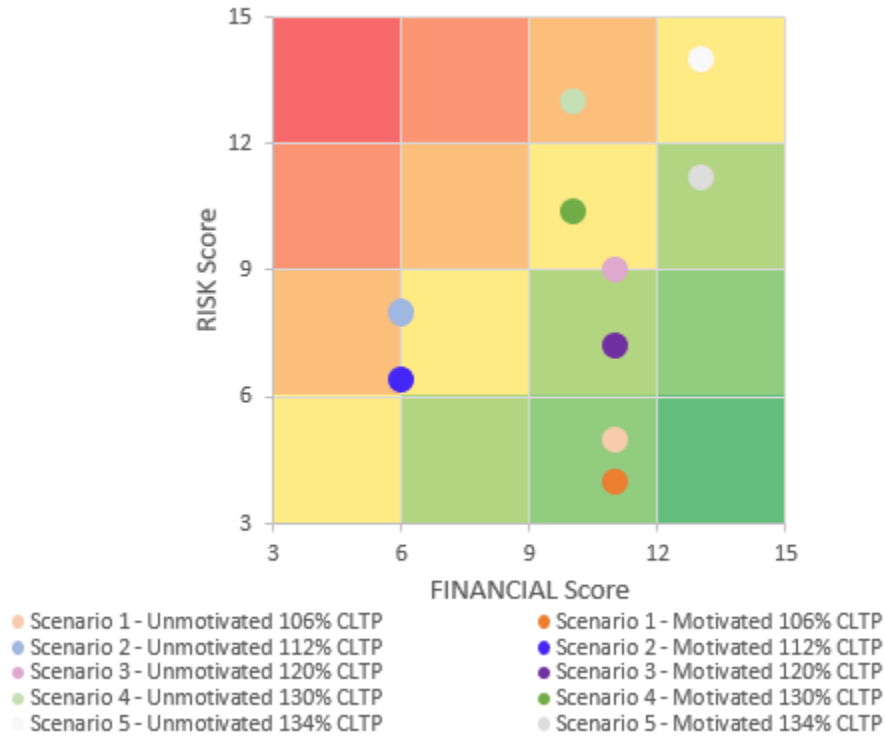


Figure C-4
Power uprate level heat map

C.3 Conclusions and Recommendations

The result of this study indicates that the optimum power uprate level for Buzzards Beach NPP is 134% of CLTP (an additional ~340 MWe) at an estimated cost of \$1B considering existing LCM and incremental power uprate costs. This power uprate level was selected over 106%, 112%, 120%, and 130% of CLTP based on the modifications required to successfully implement the uprate, company objectives, market forecasts, project risk, and financial analyses.

There are some power uprates that have similar financial scores with lower risk scores than the recommended power uprate level of 134% of CLTP, but these do not provide the electrical power that the utility requires and, therefore, were not selected.

The next step for Buzzards Beach NPP is to perform key alternative analyses for Projects 5a, 6b, 8a, and 9a, which were associated with complex modifications and/or long lead items. This effort will help refine the ROM and scope of work for the power uprate.

C.4 Appendices

The feasibility study contains the following appendices:

- Appendix 1, which identifies key SSCs impacted by power uprate
- Appendix 2, which lists these key SSCs for which there is an existing LCM project
- Appendix 3, which summarizes the margin assessment for SSCs that are impacted by power uprate but do not have a planned LCM upgrade

Appendix 1: Identification of Key SSCs Impacted by Power Uprate

The following table identifies the key SSCs impacted by power uprate. SSCs that are not significantly impacted by a power uprate (that is, those denoted by *N* in Appendix 1) should be excluded from further evaluation.

	Item	Owner/Lead	Significant Uprate Impact? ¹ (Y/N)	Rationale
Condensate System	Condensate booster pumps	Engineer A	Y	Increased system flow
	Main condenser	Engineer B	Y	Increased heat duty
	Steam jet air ejector	Engineer C	N	Power level not expected to significantly impact steam jet air ejector
	Condensate filter demineralizer	Engineer C	Y	Increased system flow, increased operating temperatures
	Low-pressure FWBs	Engineer B	Y	Increased heat duty, increased system flows
	Condensate system piping	Engineer G	N	FAC not expected to increase significantly
Main Steam	Moisture separator reheater	Engineer D	Y	Increased system flows, increased operating temperatures
	Relief valves	Engineer E	Y	Increased system flow
	MSIVs	Engineer E	Y	Increased system flow
	Main generator	OEM	Y	Increased power output
	Steam generator	OEM	Y	Increased heat duty, increased system flow

MSIV = main steam isolation valve

This table is for example only. The actual feasibility study report table would have many more SSC entries.

¹ A significant uprate impact for a system, program, or evaluation is an upgrade/replacement as a result of the uprate that will require an investment of \$1M or more.

Appendix 2: LCM Screening

For the key SSCs impacted by power uprate, the following table identifies these components for which there is an existing LCM project along with the year of planned modification.

	Item	Owner/Lead	Significant Uprate Impact? ¹ (Y/N)	Rationale	Planned LCM Upgrade/ Replacement? (Y/N)	LCM Project (ID and Description)	LCM Project Implementation Year
Condensate System	Condensate booster pumps	Engineer A	Y	Increased system flow	N	N/A	N/A
	Main condenser	Engineer B	Y	Increased heat duty	N	N/A	N/A
	Condensate filter demineralizer	Engineer C	Y	Increased system flow, increased operating temperatures	N	N/A	N/A
	Low pressure FWHs	Engineer B	Y	Increased heat duty, increased system flows	N	N/A	N/A
Main Steam System	Moisture separator reheater	Engineer D	Y	Increased system flows, increased operating temperatures	Y	LCM-01: MSR New Chevron Design	2026
	Relief valves	Engineer E	Y	Increased system flow	N	N/A	N/A
	MSIVs	Engineer E	Y	Increased system flow	N	N/A	N/A
	Main generator	OEM	Y	Increased power output	Y	LCM-06: Stator Rewind	2025
	Steam generator	OEM	Y	Increased heat duty, increased system flow	N	N/A	N/A

MSIV = main steam isolation valve

This table is for example only. The actual feasibility study report table would have many more SSC entries.

¹ A significant uprate impact for a system, program, or evaluation is an upgrade/replacement as a result of the uprate that will require an investment of \$1M or more.

Appendix 3: Margin Assessment

The following table summarizes the margin assessment for SSCs that are impacted by power uprate but do not have a planned LCM upgrade. The table identifies the critical parameters for each component along with associated operating, TS, and design limits and the power level at which the design limit is exceeded. Limiting parameters are highlighted in blue.

System	Item	Critical Parameter	Current Operating Conditions	Operating/ Test Limit	Operating Limit Impacted by Uprate? (Y/N)	TS Limit	TS Limit Impacted by Uprate? (Y/N)	Design Limit	Maximum Power Uprate ²	Comments
Condensate System	Condensate pumps	NPSH			Note 1				135%	N/A
		BEP			Note 1				132%	N/A
		TDH			Note 1				N/A	Need sufficient head for the desired flow rate
		Flow rate			Note 1				N/A	
		Motor output power			Note 1				106%	N/A
	Main condenser	Steam flow velocity			Note 1				120%	Governs steam erosion
		Circulating water flow rate			Note 1				125%	N/A
		Backpressure			Note 1				125%	N/A
		Heat removal capacity			Note 1				127%	N/A
	Condensate demineralizers	Resin temperature			Note 1				111%	Limited by operating limit in summer months
		Flow rate			Note 1				100%	N/A

Example Feasibility Study: Buzzards Beach Nuclear Power Plant Power Uprate Feasibility Study

System	Item	Critical Parameter	Current Operating Conditions	Operating/ Test Limit	Operating Limit Impacted by Uprate? (Y/N)	TS Limit	TS Limit Impacted by Uprate? (Y/N)	Design Limit	Maximum Power Uprate ²	Comments
	Low-pressure FWHS	Tube-side nozzle velocity			Note 1				125%	N/A
		Tube-side tube velocity			Note 1				200%	N/A
		Tube-side pressure drop			Note 1				156%	N/A
		Design pressure			Note 1				127%	N/A
		Design temperature			Note 1				162%	N/A
		FIV from increased shell side flow over tubes			Note 1				129%	N/A
		Steam inlet nozzle velocity			Note 1				143%	Design limit varies with shell side pressure
		Drain inlet nozzle mass flux			Note 1				125%	N/A
		Drain nozzle velocity			Note 1				112%	N/A
		Design pressure			Note 1				128%	N/A
		Design temperature			Note 1				159%	N/A

Example Feasibility Study: Buzzards Beach Nuclear Power Plant Power Uprate Feasibility Study

System	Item	Critical Parameter	Current Operating Conditions	Operating/ Test Limit	Operating Limit Impacted by Uprate? (Y/N)	TS Limit	TS Limit Impacted by Uprate? (Y/N)	Design Limit	Maximum Power Uprate ²	Comments
Main Steam	Relief valves	Setpoint pressure	Note 1						113%	N/A
		Flow rate capacity	Note 1						133%	N/A
	MSIVs	Stroke time	Note 1						135%	Design limit stroke time is the fastest stroke time achievable by the valve.
		Stem thrust	Note 1						130%	Need sufficient thrust to meet stroke time criterion
Steam generator		Thot	Note 1						156%	N/A
		Steam generator pressure (shell side)	Note 1						147%	N/A
		Tube vibration	Note 1						130%	FIV Concern
		Heat transfer capacity	Note 1						142%	N/A
		Water level stability	Note 1						151%	N/A
		Moisture carryover	Note 1						161%	N/A
		Primary separator flow rate	Note 1						134%	N/A

MSIV = main steam isolation valve

Note 1:

This table is not a comprehensive listing of components and critical parameters. Instead, it is intended to provide an example margin assessment table for Appendix C.

² Maximum power uprate levels are fabricated numbers for illustrative purposes and are not intended to reflect real limits of SSCs. The maximum power uprate that an SSC can tolerate will depend on plant specific system and component design.

This table is for example only. The actual feasibility study report table would have many more SSC entries.

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EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com