ELECTRIC POWER RESEARCH INSTITUTE

THE ECONOMICS OF NUCLEAR PLANT MODERNIZATION IN U.S. MARKETS

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Abstract

Announcements of nuclear power plant retirements throughout the world have increased amid sustained low gas prices, market pressure from renewables, slow demand growth, and uncertainty about future policies. Although market and policy changes can have significant impacts, nuclear power plant owners and operators may decide to undertake modernization efforts to lower costs of plant operations and thereby improve their economic competitiveness in a changing landscape.

This white paper describes a framework for assessing the economic value of modernizing the existing nuclear fleet in the United States and demonstrates how this value depends on future market, policy, and plant-specific conditions. *Modernizing*, in this context, means applied process improvements (for example, risk-informed decision making) and technologies (for example, digital monitoring and automation) to reduce plant operating costs. The goal of this analysis is not to provide precise estimates but to propose a structure for assessing the value of nuclear modernization and to offer order-of-magnitude approximations. Asset owners and operators can further refine these estimates using proprietary data or additional plant-specific assumptions. Although this paper focuses on U.S. markets, the methods used are applicable in any energy market in the world.

Given the data and assumptions used in this paper, initial estimates suggest that many nuclear plants can justify investments of more than $100 million to modernize and reduce fixed operations and maintenance (FOM) capital costs by 25%. The break-even value of modernization varies significantly by plant, though it is typically higher for larger multi-unit plants. Cost reductions from modernization and market conditions also impact break-even value estimates, and these values tend to be higher under more favorable market conditions for nuclear, such as carbon pricing and higher natural gas prices. Premature retirements are a significant investment risk and driver of break-even values, but modernization may delay some retirements, which increases the value of modernization efforts.

Introduction

Nuclear power plants generated roughly a fifth of U.S. electricity in 2017 and more than half of its emissions-free power. However, pressures such as sustained low natural gas prices, renewable deployment, and slow demand growth have lowered wholesale power prices and revenues to existing nuclear plants (Jenkins, 2018; Bistline et al., 2018; U.S. DOE, 2017). These factors have led to the closures of some nuclear plants, announced retirements, and policy interventions to prevent additional closures (U.S. DOE, 2017). This economic pressure is not limited to the United States, because nuclear plants throughout the world are under similar stress.

Table 1 shows the closed nuclear power plants and announced retirements in the United States, the resulting 5274-MW capacity lost since 2013, and the impending loss of more than 11,000 MW of additional capacity (more than a tenth of the current nuclear fleet). Because these decisions are irreversible, retirements have important implications for electric sector costs, greenhouse gas emissions, local economies, and criteria pollutants.

One key driver of nuclear retirements is the underlying economics of individual power plants. In simplest terms, a plant may decide to retire if the cost to generate electricity exceeds the cost of buying power on the market. These assessments become more complicated because of changes in costs and revenues over time, as well as periodic lumpy expenditures for refueling, maintenance, and upgrades. This time dimension is captured through net present values (NPVs) for plants by summing cash flows with an assumed time value of money. Additionally, uncertainty about future benefits and costs impacts retirement decisions.

In 2017, Idaho National Laboratory (INL) estimated that nearly 70% of U.S. nuclear units had a revenue gap in 2016 and that $15/MWh would close this gap for most plants. This difference could come by increasing revenues (for example, selling products into new markets, such as process heat, or receiving policy support through zero emissions credits) and/or by decreasing costs (for example, through modernization initiatives).

Although nuclear plants in many regions face near-term revenue shortfalls relative to current operating costs, one approach to improving the economic competitiveness of plants is to undertake modernization efforts to lower costs. Modernizing existing nuclear power plants can leverage technological innovation to investigate potential improvements to plant operations, including digital upgrades, automation, monitoring, business process improvements,

Table 1
Closed and announced nuclear power plant retirements in the United States (updated December 2018)

Reactor(s)	Capacity (MW)	State	Closure Year	Status
Crystal River 3	860	FL	2013	Retired
San Onofre 2/3	2150	CA	2013	Retired
Kewaunee	566	WI	2013	Retired
Vermont Yankee	612	VT	2014	Retired
Fort Calhoun	478	NE	2016	Retired
Oyster Creek	608	NJ	2018	Retired
Pilgrim	678	MA	2019	Planned
Three Mile Island	803	PA	2019	Planned
Davis-Besse	894	OH	2020	Planned
Duane Arnold	619	IA	2020	Planned
Indian Point 2/3	2051	NY	2020/21	Planned
Perry	1240	OH	2021	Planned
Beaver Valley 1/2	1834	PA	2021	Planned
Palisades	787	MI	2022	Planned
Diablo Canyon	2240	CA	2024/25	Planned
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and risk-informing decisions. These modernization efforts are aimed at lowering the costs of operating plants without compromising nuclear safety, security, or reliability and keeping these units economically competitive for longer time frames.

The objective of this white paper is to propose a framework for estimating the maximum willingness to pay (or *break-even value*) for a modernization investment to reduce an existing nuclear plant's non-fuel costs and to provide preliminary estimates for these break-even values. The analysis uses the Electric Power Research Institute's (EPRI's) U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN)[1] energy-economic model to quantify how modernization could alter potential revenues, costs, and retirement decisions and to evaluate variation across plants and scenarios. Asset owners and operators can refine these order-of-magnitude approximations using proprietary data or additional plant-specific assumptions. These economic estimates can then be used to inform future projects and can be compared with detailed engineering estimates of modernization costs. It should be noted that it is not the objective of this paper to describe specific activities and how they will achieve these goals. Instead, as plant modernization efforts are considered and undertaken, the estimates presented in this paper can serve as approximations for changes in net benefits.

Methods and Data

The break-even value of modernization is the maximum willingness to pay for an investment in a modernization intervention to reduce an existing nuclear plant's operating costs. Quantitatively, the break-even value for plant p (using the notation βp) is defined by calculating the NPV of cost reductions across a plant's lifetime:

$$\beta_p = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t}$$

where Ct is the reduction in nuclear costs in year t (which varies by plant and modernization level), i is the discount rate (that is, the opportunity cost of capital), and N is the years to retirement after the modernization investment. These calculations do not account for possible changes in tax- or depreciation-related cash flows resulting from modernization. The retirement year varies by plant and scenario and requires economic modeling in a framework

°[1] The US-REGEN model features regional disaggregation and technological detail of the power sector and linkages to other economic sectors. This state-of-the-art model has been used in many analyses and peer-reviewed articles (https://eea.epri.com/models.html).

like such as the one described in the following section to evaluate. Qualitatively, retirements occur when the NPV of going-forward costs exceeds anticipated market revenues.

In this analysis, modernization is assumed to lower all non-fuel operating costs, including maintenance capital and other non-fuel FOM costs.[2] These costs vary significantly by plant and by data source, as shown in Figure 1.

Maintenance capital costs (defined as expenditures on durable equipment for applications such as uprates, extended operations, regulatory requirements, and sustaining operations) are based on Electric Utility Cost Group (EUCG) values averaged between 2002 and 2014.[3] Model data are the sum of maintenance capital costs and non-maintenance FOM costs based on the ABB Velocity Suite (which come from production costs filed by investor-owned utilities through Federal Energy Regulatory Commission Form 1). Operating costs also account for decommissioning and waste disposal costs. Note that, although nuclear's short-run marginal costs of operation are low, these non-fuel costs are higher than many other generators, largely due to the higher skilled labor intensity.[4]

The maximum willingness to pay (that is, break-even amount of capital a plant could spend under a given set of conditions) for modernization depends critically on non-fuel cost assumptions before modernization is undertaken. Therefore, this type of analysis should be refined by plant owners and operators to calculate break-even values for plant-specific modernization interventions.

Other cost and performance parameters for nuclear power plants and other generators in the existing fleet are also based on ABB Velocity data. For this analysis, if a plant has announced its closing but has not yet retired (see Table 1), it is included in analysis with a 60-year lifetime.

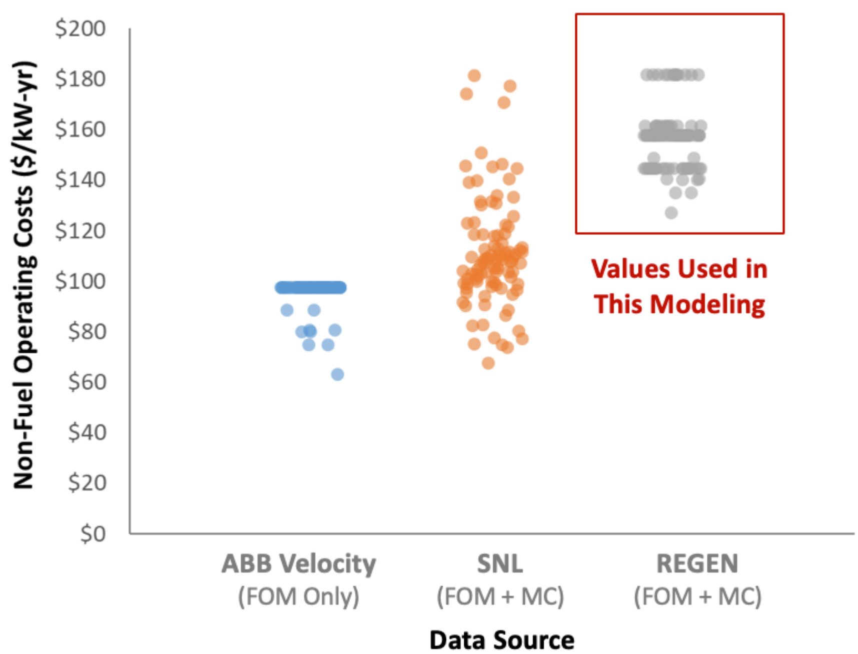

Figure 1
Non-fuel operating costs costs ($ per kW-capacity per year) for each nuclear unit in the U.S. (dots) across three data sources ("FOM" refers to non-capital fixed operations and maintenance costs, "MC" refers to maintenance capital costs)

[2] *Non-fuel costs* will be used for the remainder of the white paper as shorthand to refer to the sum of maintenance capital costs and all non-capital FOM costs. Future work should examine the impacts of lowering nuclear fuel cycle costs and of additional maintenance and investment associated with modernization after the initial period.

[3] EUCG maintenance capital data exhibit cost differences between single- and multiunit sites ($84 versus $60/kW-yr for pressurized water reactors, respectively, and $64 versus $47/kW-yr for boiling water reactors).

[4] A typical nuclear power plant has between 600 and 1000 on-site employees (EUCG, 2010), which would be approximately 0.6–1 employees per MW output for a 1-GW plant. A typical natural gas-fired 2x1 combined-cycle plant of 600–900 MW has staffing levels of approximately 0.03–0.04 direct employees per MW (EPRI, 2018b).

Model and Scenarios

US-REGEN Framework

The U.S. Regional Energy, GHG, and Economy (US-REGEN) model is a detailed energy-economic analysis framework developed, maintained, and applied by EPRI's Energy and Environmental Analysis Group. The REGEN family of models is designed to capture the physical and economic constraints associated with investment, dispatch, and integration of variable renewable energy and other grid-connected assets with extensive spatial, temporal, and technological detail while also accounting for long-term investment planning and regional interactions (Blanford et al., 2018).

The model is solved as an intertemporal optimization through 2050 with five-year time steps with the intention of simulating a competitive equilibrium in energy and capacity markets. In each time step, the 15-region model makes decisions about capacity (for example, new investment, retrofits, or retirements) and dispatch to meet energy and capacity demand for generation and inter-region transmission. It uses a bottom-up representation of power generation capacity and dispatch across a range of intra-annual time segments chosen to reflect the joint variability of load and renewable resources. It models transmission capacity between regions and requires that generation and load plus net exports and line losses balance in each time segment and for each region. The model can be used to evaluate the implications of alternative scenarios for key inputs such as technology costs and availability, fuel market prices, policy constraints, and load growth projections.

Additional information about US-REGEN's structure, data, and assumptions is available in the detailed model documentation (EPRI, 2018a). Other applications of US-REGEN are illustrated in a range of reports and peer-reviewed articles: https://eea.epri.com/models.html.

Scenarios

The break-even value of modernization interventions is evaluated for three conditions. This includes a reference (business-as-usual) cost scenario and two scenarios where plant modernization reduces FOM costs by 25% and 50% to understand potential revenue, cost, and retirement impacts across different plants in the existing nuclear fleet. These changes are combined with other cost and revenue estimates from EPRI's US-REGEN capacity planning and dispatch model to calculate changes in profitability for individual plants.

To understand how the break-even value of modernization varies across different market and policy conditions, the analysis evaluates the break-even value under the following four sensitivities about natural gas prices and CO_2 policy:

1. Reference (on-the-books only) policies and reference natural gas prices, based on the Annual Energy Outlook 2017 fuel prices (shown in Figure 2)
2. Reference policy and low gas prices (based on NYMEX Futures)

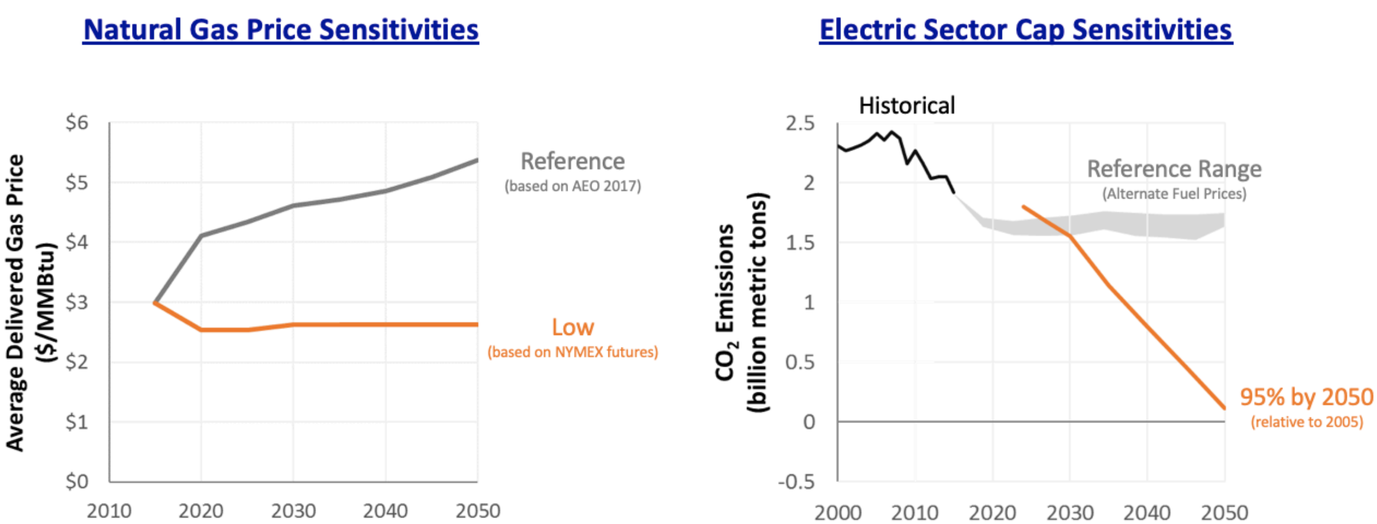

Figure 2
Natural gas price sensitivities (left) and CO_2 policy sensitivities (right)

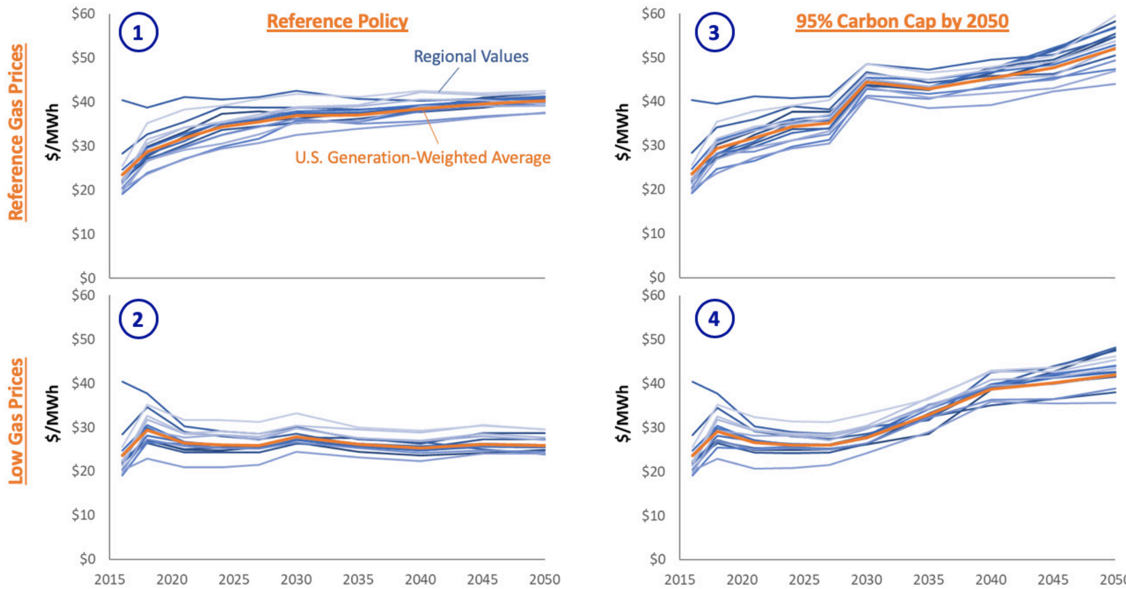

Figure 3
Wholesale regional and national electricity prices over time for the four policy and gas sensitivities:
1. Reference policy and gas prices
2. Reference policy and low gas prices
3. 95% CO_2 cap with reference gas prices
4. 95% CO_2 cap with low gas prices

3. National CO_2 cap reaching 95% reductions by 2050 relative to 2005 levels[5] and reference gas prices (shown in Figure 2)

4. National CO_2 cap and low gas prices

These sensitivities represent key sources of future uncertainty.

All sensitivities assume load growth and fuel prices (including uranium), according to the U.S. Energy Information Administration's Annual Energy Outlook 2017. No forced retirements for existing coal units are assumed, though retirements can occur for economic reasons at any time, and announced retirements have been incorporated in the model database. Technology costs for new investment are based on EPRI's Integrated Technology Generation Options report (EPRI, 2017) with updates to wind and solar generators. State renewable portfolio standards and other climate policies (for example, Regional Greenhouse Gas Initiative in the Northeast and AB-32 in California) are included. Federal regulations and tax incentives, such as production and investment tax credits and Clean Air Act §111(b) New Source Performance Standards, are incorporated in all sensitivities. The discount rate is 5%.

Figure 3 illustrates the impacts of these sensitivity analysis assumptions on regional and national wholesale power prices, which are outputs from the US-REGEN model. The profitability outlook for individual plants hinges on expectations for long-run revenues, which critically depend on policy and market assumptions. Prices trend upward in the mid to long term due to assumptions about rising gas prices in the reference, though the magnitude differs considerably by region and sensitivity. However, the case with reference policies and low gas prices leads to flat or declining power prices and, as a result, profitability challenges for nuclear power plants.

Caveats

When viewing model results, it is important to keep in mind that analyses from energy-economic models such as US-REGEN are not intended to be interpreted or used as forecasts. Insights come by asking what-if questions, running a wide variety of sensitivities, and comparing the results. Key uncertainties in this decision context are policy interventions, natural gas prices, and technological change, which can impact outcomes. This exploratory analysis is intended only to investigate the dimensions of the problem and not to predict individual plant decisions. As such, individual plant-level

[5] This sensitivity assumes aggregate U.S. reduction consistent with former Clean Power Plan goals through 2030 (reaching 32% below 2005 levels in 2030) and then linear reductions thereafter to meet the 2050 target.

outputs are not labeled to discourage overinterpretation of model results. Accurate plant- or reactor-level data are difficult to obtain, and individual plants may vary from average values as a result of a range of site-specific considerations. Nuclear power plant owners and operators are encouraged to conduct additional analysis that accounts for plant-specific considerations.

Results: Example Calculations for a Single Plant

Before comparing results across the entire fleet, it is instructive to consider a stylized example for a single plant. For simplicity, assume a 1-GW plant with total annual fixed costs (including maintenance capital) of $150/kW-yr. This plant undertakes a modernization initiative in 2020, which reduces non-fuel costs by 25%. This modernization would lead to cost savings of 25% * $150/kW * 1 GW = $37.5 million per year. Cash flows over time are discounted at a 5% rate, as shown in Figure 4.

The break-even value of modernization is the NPV of cost savings over the lifetime of the plant, which equals the maximum willingness to pay initially (in 2020) to achieve these 25% cost reductions relative to the baseline. For this example, where the plant is assumed to remain online through 2050, the break-even value is approximately $600 million (see Figure 5). If the plant were to retire in 2025 instead, the break-even value would shrink from $600 million to $200 million.

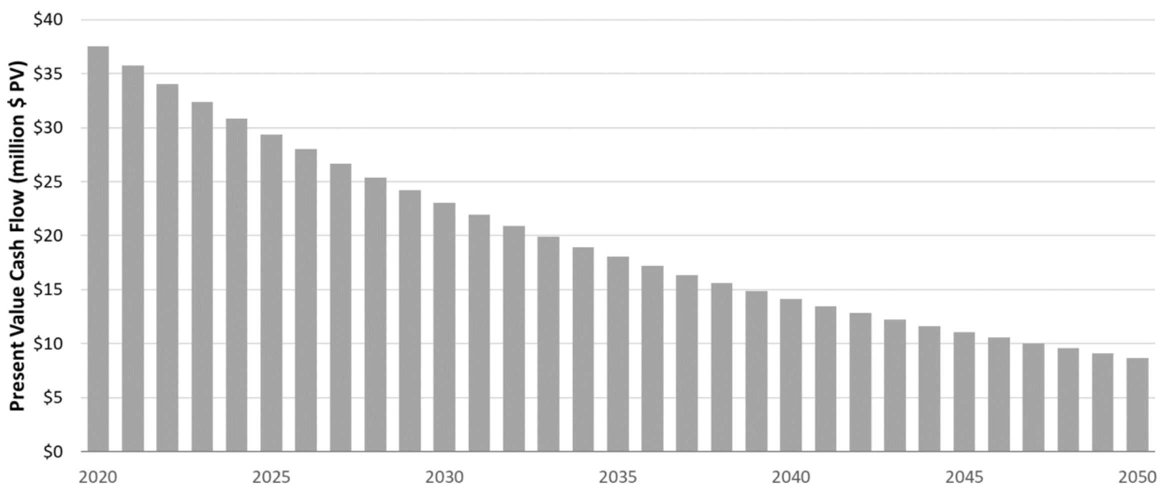

Figure 4
Stylized plant modernization example with the present value of cost savings over time for a 1-GW plant, $150/kW-year non-fuel costs, 25% cost reduction, and 5% discount rate

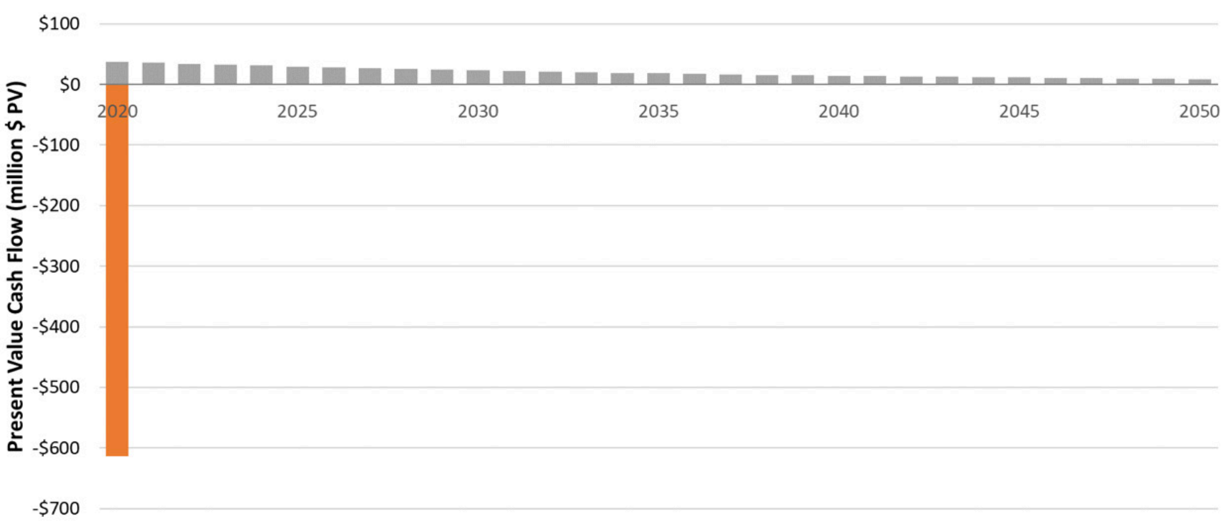

Figure 5
Stylized plant modernization example with break-even value (orange) for a 25% cost reduction

These break-even value estimates are sensitive to the magnitude of cost reduction through modernization, discount rate, non-fuel costs, and anticipated retirement year. Note that these estimates do not include changes in tax- or depreciation-related cash flows from modernization.

Figure 6 shows revenues and costs for an example plant before and after modernization to reduce costs by 25%. For this specific plant and these economic conditions (reference policies and gas prices), net operating margins would be negative until 2025 without modernization, but the 25% reduction in non-capital FOM and maintenance capital costs avoids operating at a loss in 2020 and increases profitability thereafter.

Results: Value of Modernization Across Plants

The break-even value of modernization for nuclear power plants varies considerably across market conditions and individual plants. Figure 7 shows variation in the break-even value for modernization interventions that reduce costs by 25%. Given the data and assumptions listed in previous sections, these estimates suggest that many nuclear plants would be able to justify investments of more than $100 million to modernize and reduce costs by 25%. Plant size is a key variable in plant-specific values for the same policy and market conditions (for example, a three-unit site would be at the high end of the range owing to its size). Modernization is more valuable for multiunit sites than for single-unit sites.

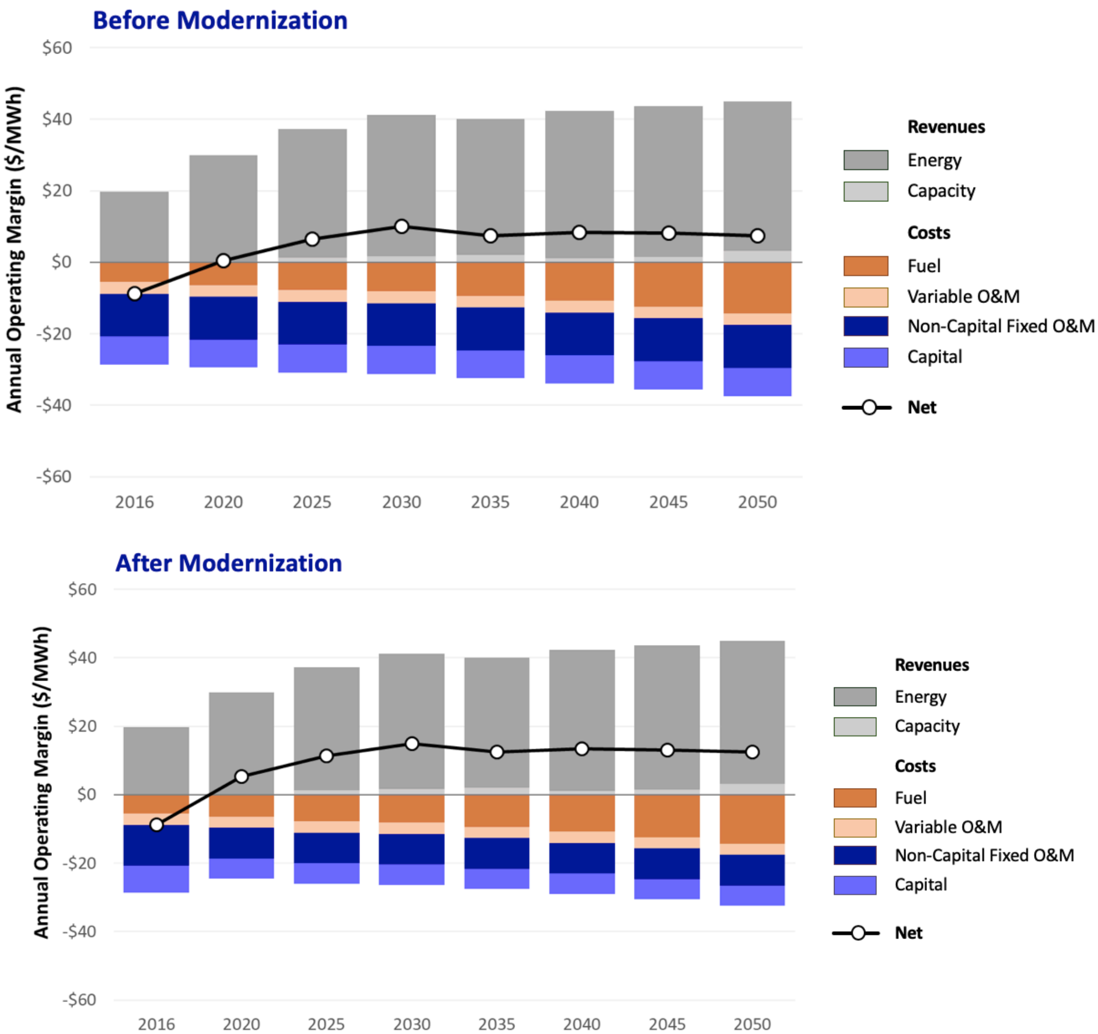

Figure 6
Operating margins by revenue and cost category for an example nuclear plant under reference policies and gas prices before modernization (top panel) and after a 25% cost reduction (bottom panel) in non-fuel costs (that is, maintenance capital and other non-fuel FOM costs)

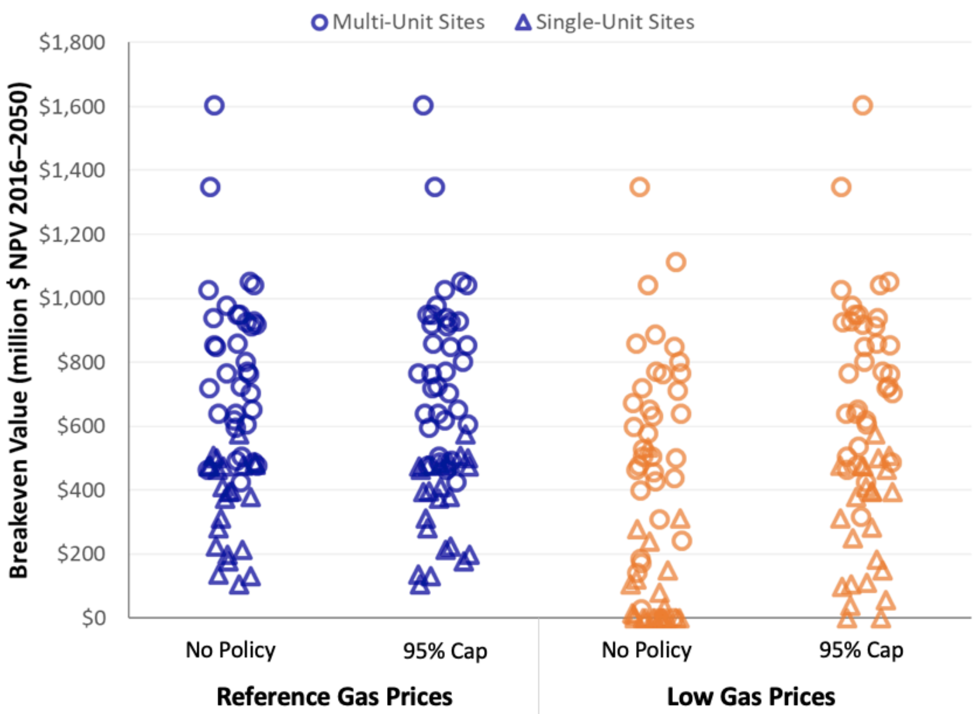

Figure 7
Break-even value of nuclear plant modernization (million $ NPV) by sensitivity (columns) and by nuclear plant (individual points) with 25% cost reduction

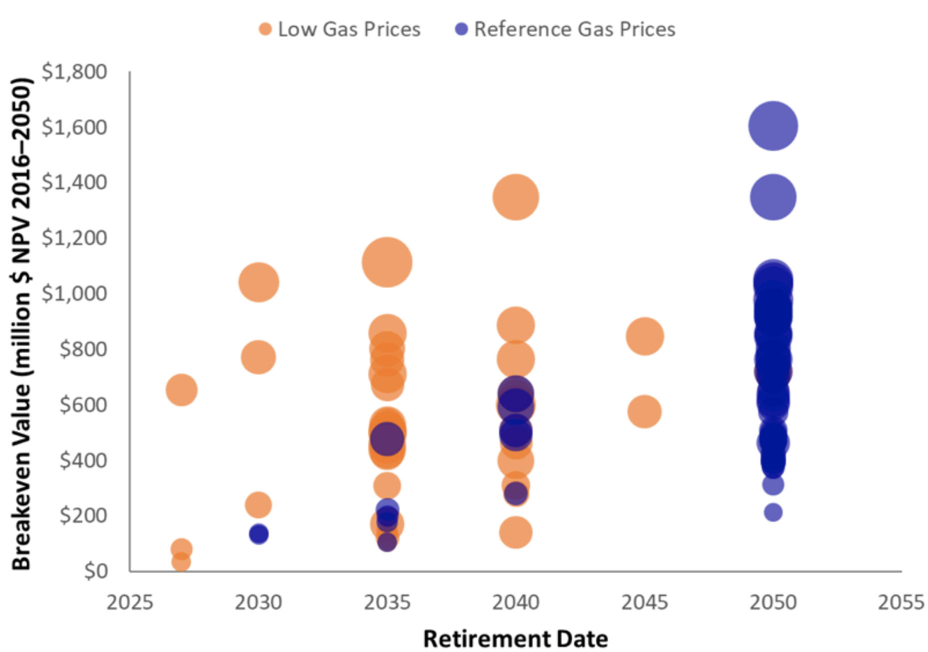

Figure 8
Break-even value of nuclear plant modernization (million $ NPV) and retirement dates for nuclear plants (individual points with sizes scaled to plant capacity) with 25% cost reduction

The break-even value (that is, net economic benefit) of modernization decreases for sensitivities with lower natural gas prices, because many existing nuclear plants retire earlier than conditions with higher prices. In contrast, climate policy can boost revenues and prevent earlier retirements. In this way, climate policy can increase the value of modernization for plants that would otherwise retire but does not impact the break-even value of competitive plants.

As shown in Figure 8, these sensitivities demonstrate how break-even values for modernization investments are lower for units that retire earlier. Lower natural gas prices negatively impact nuclear plant revenues, which leads to earlier economic retirements compared with a higher natural gas price environment. A corollary is that returns on modernization efforts are likely higher for multiunit sites, because retirement risks are generally lower for these plants than for single-unit nuclear plants.

Roughly a third of plants have near-zero break-even values with low natural gas prices, because these plants would retire after 2020 due to expectations that going-forward costs (even with modernization) would exceed revenues. However, even with low gas prices, more than half of the fleet would expect a 25% cost reduction to yield at least $400 million in savings over the plant's lifetime (assuming a 5% discount rate).

Across different levels of cost reductions from modernization, Figure 9 suggests that the break-even value increases nearly linearly with increasing cost reductions. This relationship is linear for plants where cost reductions do not impact retirement decisions. However, the kinks in the value curves for plants under the low gas price sensitivity reflect avoided plant retirements from modernization.

Discussion and Next Steps

This white paper describes a framework for assessing the economic value of modernizing the existing nuclear fleet and demonstrates how this value depends on future market, policy, and plant-specific conditions. Given the data and assumptions used here, initial estimates suggest that many nuclear plants would be able to justify investments of more than $100 million to modernize and reduce non-fuel costs by 25%.

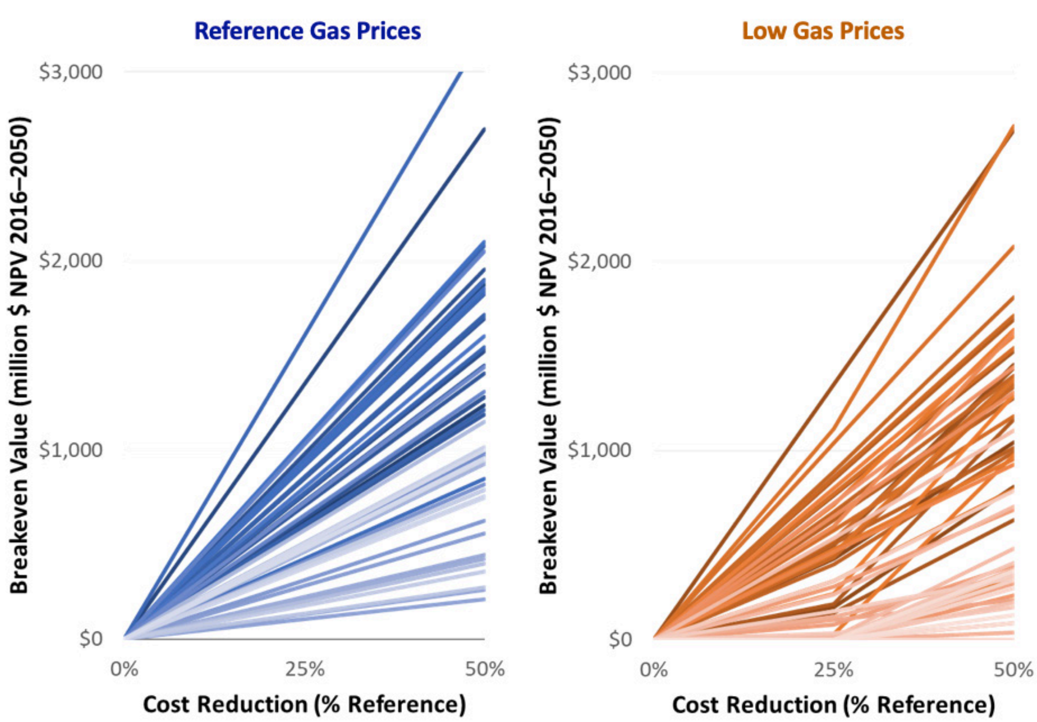

Figure 9
Break-even value of nuclear plant modernization (million $ NPV) by gas price sensitivity (panels) and by nuclear plant (individual lines) across different cost reduction levels

The break-even value of modernization varies significantly by plant, though it is typically higher for larger multiunit plants. Cost reductions from modernization and policy/market environment also impact break-even value estimates, and these values tend to be higher under more favorable market conditions for nuclear, such as carbon pricing and higher natural gas prices. Premature retirements are a significant investment risk and driver of break-even values, but modernization may delay some retirements, which increases the value of modernization efforts.

Overall, the profitability outlook for existing nuclear plants hinges on long-run market and policy prospects. Expectations about gas prices and carbon pricing are important (as are additional state policy interventions that are not modeled here), in addition to efforts to lower nuclear power plant non-fuel costs. Earlier nuclear plant retirements risk underperformance in reaching emissions reductions targets (Roth and Jaramillo, 2017), but modernization could help to extend economic lifetimes and reduce emissions.

The goal of this analysis is not to provide precise estimates but to propose a framework for assessing the value of nuclear modernization and to offer order-of-magnitude approximations, which asset owners and operators can refine using proprietary data or additional plant-specific assumptions. Future work should compare these break-even value estimates with detailed engineering assessments of modernization costs to perform a benefit-cost assessment. These estimates should be compared with investment alternatives faced by decision makers. Additional sensitivities related to the discount rate, explicit consideration of uncertainty, and other types of policies should be investigated in future work.

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Nuclear Plant Modernization

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